Demonstration of a novel single-mode hybrid silicon microlaser

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***Abstract*—We present the first experimental demonstration of a novel class of hybrid III-V on silicon microlasers. This new type of laser revolves around the concept of resonant mirrors: two silicon cavities, directly coupled to the III-V laser mesa, provide high, narrow band reflection over a short distance. This results in a device that measures only 55 μm by 2μm and shows single-mode laser emission with a SMSR of 39 dB.**

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

I. INTRODUCTION

Over the past decade, silicon photonics has emerged as a major technology platform for photonic integrated components and circuits. Combining the mature fabrication processes inherited from CMOS with the high refractive index contrast between the silicon waveguide core and its cladding allows for unprecedented miniaturization of passive optical components. Unfortunately, silicon has an indirect bandgap, making it extremely difficult to use it as a laser gain medium. Amongst the different solutions that have been proposed to integrate coherent light sources directly onto the silicon die, one of the most promising approaches is to bond a slab of direct bandgap material (i.e. a III-V compound) onto the silicon die [1]. After bonding, a series of lithography and etching steps are performed on the slab to create the laser cavity. DBR- and DFB-lasers have been demonstrated [2], [3] on this platform where the laser mode is confined to the silicon layer and only its evanescent tail overlaps with the active III-V layer. This yields single-mode devices with high optical output, but the structures are large and require a fairly high threshold current ($> \ 20\,mA$). On the other hand, microdisk lasers were demonstrated [1] with small form-factors (disk radius $< 10\,\mu m$) and low lasing threshold ($< 1\,mA$) but they suffer from a low side-mode suppression ratio (SMSR) and mode hopping. In this work, we present the very first experimental demonstration of a novel III-V on silicon microlaser that is both small and offers intrinsic single-mode laser operation.

II. RESONANT MIRRORS

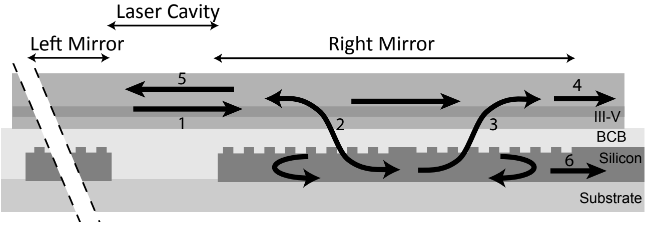

Fig. 1. Schematic side-view of the operation of the resonant mirror laser.

The proposed laser structure consists of a III-V wire with two silicon cavities underneath, one under each end of the III-V wire [4]. Such a silicon cavity can be a grating waveguide with a phase-shifting section in the center to create a defect-resonance. Figure 1 shows a schematic side-view of the proposed laser. Light is generated and amplified in the III-V wire where it is fully confined. As the light approaches the end of the III-V wire (**1** in figure 1), a small part of the light couples to the silicon cavity underneath (**2**). For the wavelengths close to the silicon cavity's resonance wavelength, power will start to build up inside the silicon cavity and eventually a significant amount of optical power will couple back into the III-V wire. The light coupling back co-directionally to the incident light (**3**) will interfere destructively to the latter, resulting in zero transmission (**4**). On the other hand, the light coupling back counter-directionally to the incident light (**2**) will provide feedback into the III-V wire (**5**), required to establish laser operation. Light can easily be extracted to an output waveguide by tapping a small amount of the power built-up in the silicon cavity to an external waveguide (**6**).

Because the power-buildup only occurs close to the silicon cavity's resonance wavelength, the reflection bandwidth of this type of mirror is very narrow ($< 5\,nm$). Since the reflection of such a mirror can be very high ($> \ 90\,\%$) and the laser mode is confined to the III-V wire, which maximizes the modal gain, the length of the III-V wire can be reduced to make sure only one longitudinal resonance of the III-V cavity lies within the reflection bandwidth of the mirror, yielding an intrinsically single-mode laser with a short length. Moreover, all the critical processing steps are performed in the silicon layer and no ultra-thin bonding layers are required. In fact, the design is very tolerant towards the thickness of the bonding layer, which only influences the reflection bandwidth.

III. Experimental Results

In this first optically pumped prototype, the silicon cavities are $1.6\,\mu m$ wide, $220\,nm$ high strip waveguides with $70\,nm$ deep periodic grating corrugations. Each silicon cavity consists of 60 periods with a defect in the middle to support a resonance near the grating's Bragg wavelength. The two grating cavities are separated by $20\,\mu m$. The III-V wire above is $2\,\mu m$ wide and around $55\,\mu m$ long. It consists of an $80\,nm$ thick InGaAsP bulk active layer, sandwiched between two InP cladding layers and the total thickness of the III-V stack is around $250\,nm$. The III-V layer was bonded onto the silicon die using DVS-BCB bonding with a $250\,nm$ thick bonding layer between the top of the silicon waveguide and the bottom of the III-V waveguide. Figure 2a shows a top-view SEM image of the device. The silicon mirror structures are masked by the III-V overlay but the white dashed boxes indicate the location and longitudinal extent of both silicon grating cavities. In this particular case, both mirrors are identical and both have a silicon output waveguide. The tapered edges of the III-V wire are intentionally patterned to avoid back-reflection from the III-V waveguide's facets.

The devices were measured at room temperature by illuminating each device individually from the top with an $800\,nm$ pump laser. In this experiment we used $10\,ns$ pulses with $10\,mW$ peak power and a repetition rate of $1.5\,\mu s$. Using an objective and a cylindrical lens, the shape of the illuminating spot was engineered to match the shape of the III-V waveguide. The output of the laser is coupled to a silicon waveguide which guides it towards a grating coupler. From there, a cleaved fiber leads the laser output to a spectrometer equipped with a nitrogen cooled InGaAs line camera.

The inset of figure 2b depicts the optical output power as a function of the input power, clearly showing the laser threshold. Taking into account the highly inefficient optical pumping, we estimate the power consumption of this laser at threshold to be less than $1\,mW$. The laser peak output power is conservatively estimated to be $10\,\mu W$ and is limited by the available pump power. Figure 2b shows the output spectrum of two different lasers. The two devices are identical, only the grating period differs: $285\,nm$ in one device and $290\,nm$ in the other. This shows that the laser wavelength can be defined accurately in the silicon layer. For both devices the SMSR is more than 37 dB. As expected, there is no evidence of spurious side-modes. The spectral longitudinal mode spacing in the cavity is estimated to be around $7\,nm$, but the bandwidth of the resonant mirror is on the same order of magnitude, such that only one longitudinal mode is reflected. The duration of the pump-pulse was increased and laser operation continued up until a pulse duration of $1.2\,\mu s$ (80 % duty-cycle). This can be improved in future designs by optimizing the thermal impedance of the device.

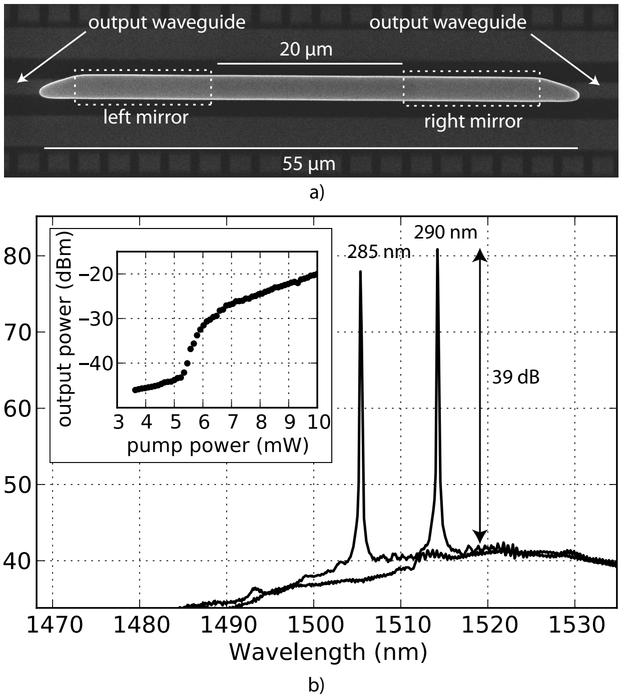

Fig. 2. a) SEM picture of the top-view of the first prototype. b) output spectrum of two lasers with different grating periods as measured through the grating coupler. *inset*: Optical output power vs pump power.

IV. Conclusions

We present the first experimental demonstration of a hybrid III-V on silicon microlaser based on resonant mirrors. The device measures only 2 μm by 55 μm and has a high SMSR, up to 39 dB. We show how the emission wavelength is determined by the properties of the silicon grating cavity. We believe that this concept, once electrical pumping is in place, will yield compact, single-mode hybrid microlasers with a threshold current of only a few mA's and precise control of the lasing wavelength.

V. Acknowledgements

The authors acknowledge partial support from IWT through the SBO-Glucosens project as well as from ERC through the InSpectra project. Yannick De Koninck thanks the research foundation Flanders (FWO) for a research grant.

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