III-V on Si distributed-feedback lasers based on exchange Bragg contradirectionnal coupling

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Abstract— **We propose a novel III-V on silicon distributed-feedback laser design that takes advantage of exchange Bragg coupling between a III-V stack and a silicon-on-insulator corrugated waveguide. Numerical simulations indicate that the structure design is compatible with bonding thicknesses up to 200 nm, which relaxes the constraints to the integration technology.**

Silicon photonics; heterogeneous integration; semiconductor laser; distributed feedback laser; mode coupling

Over the past few years, the heterogeneous integration of III-V material on Silicon-On-Insulator (SOI) wafers has appeared as a promising solution for the integration of active optical devices on CMOS substrates. Molecular bonding (using a SiO_2 layer) and adhesive bonding (using a polymer layer) have recently enabled the demonstration of several types of III-V on SOI lasers, from microdisk resonators [1] to distributed-feedback (DFB) lasers [2]. In particular, DFB lasers are attractive for wavelength division multiplexing applications due to their monomodicity. This type of laser traditionally uses an index grating along the gain material that acts as a distributed reflector. In the case of III-V on SOI lasers, the grating is preferably placed in the silicon part since the fabrication process would benefit from the maturity and the scalability of the SOI platform. Hybrid evanescent DFB lasers demonstrated by the Intel/UCSB research team have shown noteworthy results [2]. In their design, the fundamental mode of the structure is guided by the SOI waveguide and benefits from gain only on its evanescent tail which overlaps the III-V waveguide. This type of design relies necessarily on a trade-off between modal gain and coupling efficiency into the SOI waveguide. This trade-off requires the use of a very thin bonding layer between the III-V stack and the SOI (5nm in [2]) since the modal overlap on the neighbouring waveguide decreases exponentially with increasing distance between the waveguides. Such an approach can be very demanding from a technological point of view, and intrinsically leads to a device performance that is very sensitive to the bonding thickness accuracy. So as to relax the constraints on the bonding thickness and break the trade-off between modal gain and coupling efficiency, we propose to take advantage of contradirectional coupling between the III-V and the SOI eigenmodes (so called exchange Bragg coupling [3]). The originality of our design is that the grating is not only used to provide distributed feedback but also to couple the III-V and the SOI eigenmodes.

Let us consider the laser structure sketched in Fig. 1. A 580 nm-thick III-V laser stack is bonded on a SOI square-wave corrugated waveguide using a 100 nm thick SiO_2 bonding layer. The silicon thickness is set to 260 nm and the grating depth to 40 nm. The numerical simulations shown hereafter are performed in two dimensions so the structure width is considered as infinite. The laser gain wavelength is centred at 1500nm. The effective indices of the fundamental eigenmodes of the III-V and SOI waveguides are 3.16 and 2.98 respectively. Note that the SOI thickness and grating depth are both optimised so as to minimize codirectional coupling between the various modes of the structure.

The Fig. 2 represents the dispersion diagram of the whole system calculated with the plane wave expansion algorithm. Resonant contradirectional coupling between the various guided modes occurs at anticrossings points. Resonant coupling is associated with the opening of a frequency gap which amplitude increases with the coupling strength. Three distinct coupling points of interest are found at the normalized frequencies $u_1=0.158$ (a/λ), $u_2=0.162$ (a/λ) and $u_3=0.168$ (a/λ). Those coupling frequencies correspond respectively to III-V/III-V direct Bragg coupling, III-V/SOI exchange Bragg coupling and SOI/SOI direct Bragg coupling. Direct Bragg coupling corresponds to a simple mode reflection without any power transfer from a waveguide to the other. This type of coupling is used to create feedback in traditional DFB lasers.

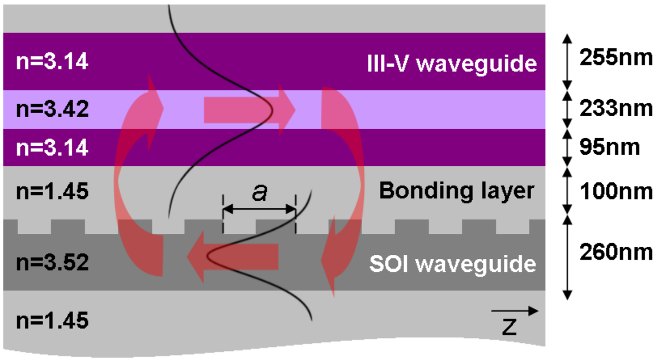

Figure 1. Schematic of a III-V laser stack bonded on a SOI corrugated waveguide. The field circulation at the exchange Bragg frequency is illustrated.

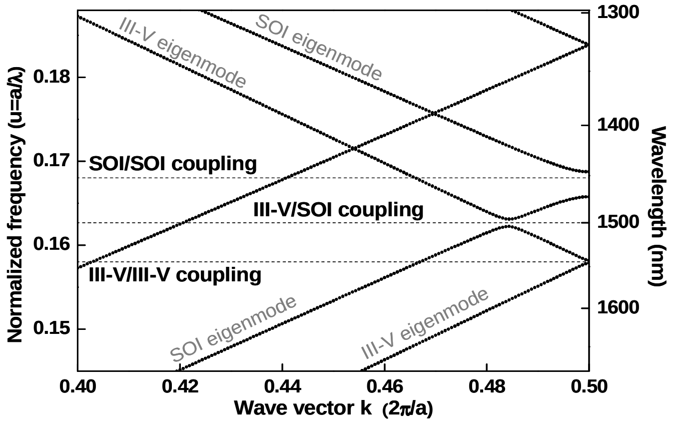

Figure 2. Dispersion diagram of the III-V on SOI structure. Wavelengths on the right axis are calculated for a grating period of 244 nm.

On the other hand, exchange Bragg coupling corresponds to a power transfer from the mode that travels in one direction in the first waveguide to the mode that travels in the opposite direction in the other waveguide [3]. Note that the exchange Bragg coupling point is not placed at the band edge of the dispersion diagram, in contrast to direct Bragg coupling. If the period of the grating is set so that the frequency u_2 is in the gain spectrum of the III-V stack, one should be able to force the optical field to circulate between the III-V and the SOI waveguide and obtain distributed feedback. This circulation of the field would allow the mode to benefit from gain on its highest amplitude part while still allowing for an efficient power extraction to the SOI waveguide. From the dispersion diagram, we calculate that a period of 244 nm would be appropriated for an emission wavelength at 1500 nm, which is achievable by deep-UV lithography.

The spectral width Δu of the gap at the exchange Bragg coupling frequency is related to the coupling constant κ by the following expression [4]:

$$\Delta u = \frac{a}{2\pi} \frac{4\kappa}{n_{gIII-V} + n_{gSOI}} \quad (1)$$

The group indices of the III-V and SOI modes $n_{gIII\text{-}V}$ and n_{gSOI} can be calculated from the slopes of the dispersion curves. From the dispersion diagram of Fig. 2, we extract $\Delta u=8.68.10^{-4}$ and $n_{gIII\text{-}V}=3.44$ and $n_{gSOI}=3.63$ which gives $\kappa=39.5\ mm^{-1}$. The same numerical simulation performed with a bonding layer thickness of 200 nm lead to $\kappa=13.2\ mm^{-1}$, stressing the tolerance of the device regarding waveguide spacing.

The spectral response of the device calculated by 2D-FDTD is shown in the Fig. 3. The structure is two hundred periods long and a quarter-wave shift defect has been added in the middle of the grating so as to break the grating symmetry and force the monomode behaviour of the DFB laser. A pulsed source is placed at the middle of the III-V waveguide and a Gaussian excitation field is launched from the right to the left of the structure. A time monitor that collects the field flowing from the left to the right is placed in the SOI waveguide. Another monitor placed one period away behind the source collects the feedback field flowing from the right to the left of the III-V waveguide. Monitor responses are normalized by the source excitation spectrum. Resonant peaks appear at the three coupling frequencies identified on the dispersion diagram of Fig. 3. The power in the III-V waveguide is more than ten times higher at the III-V/SOI coupling frequency than at the SOI/SOI coupling frequency. The latter is therefore not likely to lase due to the poor modal overlap with the gain material. On the other hand, at the exchange Bragg III-V/SOI coupling frequency, the field distribution is equally shared between the III-V and the SOI waveguides allowing for both a high amount of gain and an efficient power extraction to the SOI waveguide.

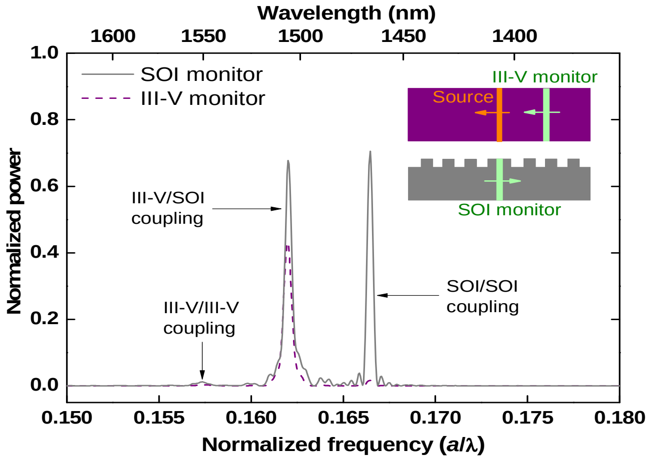

Figure 3. Spectral response of the device calculated by 2D-FDTD. The grating period is 244 nm. A quarter-wavelength shift is added in the middle of the grating. Inset : simulation layout.

In summary, we propose a new type of III-V on Si DFB laser. The distributed feedback action, which is based on an exchange Bragg III-V/SOI coupling scheme, provides an optimum trade-off between modal gain and coupling efficiency to the SOI waveguide. This optimum operation is obtained owing to the generation of a laser mode which is "ideally hybrid", since it provides an equal share of the optical field between the III-V gain material layer and the SOI waveguide. This coupling scheme is compatible with bonding thicknesses as high as 200 nm and therefore relaxes the constraints to the integration technology. FDTD simulations show that mono-mode laser emission should be obtained by using a quarter-wavelength shift in the centre of the grating just as in traditional DFB lasers.

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