Silicon Nitride External Cavity Laser With Alignment Tolerant Multi-Mode RSOA-to-PIC Interface

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Abstract—We demonstrate an external cavity laser formed by combining a silicon nitride photonic integrated circuit with a reflective semiconductor optical amplifier. The laser uses an alignment tolerant edge coupler formed by a multi-mode waveguide splitter right at the edge of the silicon nitride chip that relaxes the required alignment to the III-V gain chip and equally splits the power among its two output waveguides. Both the ground and first order mode are excited in the coupler and reach the quadrature condition at the waveguide junction, ensuring equal power to be coupled to both. Two high-quality-factor ring resonators arranged in Vernier configuration close a Sagnac loop between the two waveguides. In addition to wideband frequency tuning, they result in a longer effective cavity length. The alignment tolerant coupler increases the alignment tolerance in the two directions parallel to the chip surface by a factor 3 relative to conventional edge couplers, making it ideal for gain chip integration via pick-and-place technology. Lasing is maintained in a misalignment range of ±6 μm in the direction along the edge of the chip. A Lorentzian laser linewidth of 39 kHz is achieved.

Index Terms—Semiconductor lasers, silicon nitride, photonic integrated circuits, semiconductor optical amplifier.

I. INTRODUCTION

EXTERNAL cavity lasers (ECL) have been incorporated in systems servicing diverse applications such as coherent communications [1], spectroscopy and sensing [2], [3], swept-source coherence tomography [4] and distance metrology [5]. The versatile application fields of ECLs are owed to their low source coherence tomography [4] and distance metrology [5]. The PIC is implemented in a high-confinement PIC topology.

First results for an ECL using silicon alignment tolerant grating required for ECLs and implemented by forming a Sagnac loop. This makes them ideal for applications such as parallel single mode coupling devices, at the price of requiring two on-chip output waveguides over which the power is equally split. This makes them ideal for applications such as parallel single mode transmitters [12] or passively biased Mach-Zehnder modulators [14], [15], but also tunable back-reflectors as required for ECLs and implemented by forming a Sagnac loop. First results for an ECL using silicon alignment tolerant grating couplers were reported in [16], but this device still required a pair of ball lenses assembled together with the RSOA over the chip in a cumbersome assembly. Moreover, it did not implement wideband tunability nor featured the low linewidths shown here and did thus only provide a first proof-of-principle of the utilized PIC topology.

Here, we use an edge coupler configuration compatible with flip-chip integration technology and a pair of ring resonators in Vernier configuration for providing a wide, single mode tuning range. The PIC is implemented in a high-confinement silicon nitride (SiN) integrated waveguide platform [17] that provides both tight bends as well as reduced losses in the order
of ∼0.1 dB/cm in the C-band, enabling large on-chip delays (implemented here with high quality (Q)-factor ring resonators) and thus substantial linewidth reduction. The SiN platform has a number of advantages when it comes to the implementation of ECLs, in particular a reduced thermo-optic coefficient increasing wavelength stability relative to silicon PICs [18], as well as low waveguide losses enabling long delays and narrow linewidths [19]. In low confinement platforms, it has yielded some of the best linewidths demonstrated to date for integrated solutions [20], [21]. Besides its desirable properties for ECL implementation, the SiN platform has also served for direct integration of rare earth based gain materials [22], [23].

Here, we focus on relaxing the required placement accuracy of the RSOA in a SiN based ECL. Compared to a conventional edge coupler, the required accuracy with which the III-V gain chip has to be placed in the two directions parallel to the surface of the PIC is relaxed by a factor 3, uniquely enabling assembly with pick-and-place flip-chip technology.

The rest of this paper is organized into three sections. In Section II, we describe the silicon nitride PIC. In Section III, we report the ECL characteristics as obtained by measuring the PIC together with the RSOA, and finally, in Section IV, we conclude the paper and give an outlook on future work. In order to investigate the alignment tolerance between PIC and RSOA as quantified by ECL performance, the experiments described in Section III are performed by aligning the RSOA relative to the PIC with high-precision computer-controlled opto-mechanics. A fully packaged device with permanent RSOA attachment remains to be realized.

II. PHOTONIC INTEGRATED CIRCUIT

Fig. 1 shows a schematic of the PIC along with the RSOA and Fig. 2 a micrograph of the PIC as well as of the setup used to align it to the RSOA to obtain the ECL data in Section III. Light coupled from the RSOA is equally split between two waveguides at the output of the alignment tolerant edge coupler (ATEC), which are further coupled to each other through the two ring resonators. When the ring resonators’ resonances are tuned to overlap with each other at a single wavelength, the two rings selectively close a Sagnac loop for that resonant wavelength. The rings are designed so that most of the light remains within the laser cavity. The coupling coefficients $\kappa_{a1}$ and $\kappa_{a2}$ describing the coupling strength between the main bus waveguides (connected to the ATEC) and the rings are chosen such that between 10% and 30% (depending on the design types described below) of the optical power is routed to the two chip/laser outputs labeled as Out 1 and Out 2 at the resonance wavelengths. The other coupling sections, with coefficients $\kappa_{b1}$ and $\kappa_{b2}$, connecting the two rings with each other via a third bus, are optimized so that all the light passing through this intermediate waveguide remains inside the laser cavity. The two unlabeled output ports between Out 1 and Out 2 were included as low reflection terminations and for monitoring purposes, but nominally carry zero output power since all the power dropped from one ring into the intermediate waveguide is picked up by the other ring at the critical coupling condition and subsequently routed back to the RSOA. To reduce
unwanted back-reflection into the PIC, the output edge couplers are slanted with a 15° angle relative to the normal to the interface, as parasitic back-reflections can lead to unstable operation or an increased linewidth. Compared to straight edge couplers with back-reflections extracted to be $-14.5 \text{ dB}$ from ripples in Fabry-Perot test structures implemented for that purpose, the mode-to-waveguide back-reflections of the slanted edge couplers were measured to be reduced to $-19.5 \text{ dB}$. Slanting the edge couplers does not significantly reduce the coupling efficiency to a lensed fiber to which light is coupled at the output of the ECL, provided the latter is also aligned with a corresponding angle of 22° resulting from refraction.

The PIC was fabricated by LIGENTEC in their standard multi-project wafer (MPW) process with photonic structures fully etched in an 800 nm SiN film fabricated by high-quality low pressure chemical vapor deposition (LPCVD) and fully clad by SiO₂. Optical input-output facets of the chip are defined by a deep etch applied during chip fabrication and have thus very low roughness. They are left uncoated in the following experiments. In the next subsections, the ATEC and the Vernier structures are described in more details.

### A. Alignment Tolerant Edge Couplers

Fig. 3 shows the schematic of the ATEC. Light is first coupled into an array of 9 thin waveguides. These are 200 nm wide and spaced, center-to-center, by 700 nm. Since light exits the RSOA at an angle, also to reduce back-reflections, the waveguide array is also slanted by 13.1° to match the direction of propagation of the light after refraction. Together, the waveguides form, edge-to-edge, a 6 μm wide interface along the facet of the PIC and form the equivalent of a slab waveguide with weaker mode confinement in the vertical (y-)direction. The mode field diameter (MFD) of its supermodes, defined as the distance between the points at which the field intensity reaches $1/e^2$ of its maximum, is 2.5 μm in the y-direction and is closely matched to the vertical MFD of the RSOA, estimated from far field diffraction angles extracted from beam profile measurements, and to the MFD of the lensed fiber used for PIC characterization measurements in the following. The array of tips supports 4 transverse electric (TE) polarized supermodes with different numbers of in-plane lobes (along the x-direction), however, only the ground and first-order modes are being used, as the other modes are being filtered out by the downstream taper and interference section. The ground mode has an in-plane MFD of 4.5 μm, along the x-direction, also close to that of the RSOA but significantly larger than that of the lensed fiber used for PIC characterization. In either case, as the RSOA or lensed fiber are being displaced in the x-direction, the ground and first order supermodes are being excited with different amplitudes, but with the same phase (assuming the waist of the incoming beam is right at the interface).

The tips are then progressively tapered up from 200 nm to 400 nm, over a length of 30 μm, pulling the field into the SiN core, before being merged into a single slab. A second taper adiabatically reduces the slab width down to 1.4 μm, over a conservatively chosen length of 100 μm. The following interference section supports two TE-polarized modes, the ground and first order mode. The length of the multimode interference section (IS) is chosen such that the two lowest supermodes at the input interface of the coupler are mapped to its two modes with a 90° relative phase shift at the output waveguide junction. Finally, the light is split and routed to two 550 nm wide single-mode output waveguides that are further tapered up to 600 nm.

This leads to the two modes always reaching the waveguide junction in quadrature, irrespectively of the lateral (x-direction) displacement of the RSOA or lensed fiber at the input interface, suppressing interference and ensuring that equal power is coupled into both waveguides. This does not violate the reciprocity principle, as light is coupled to the two output waveguides with an RSOA-position-dependent relative phase. However, since the light is routed to a Sagnac loop thereafter, whose functionality does not suffer from this phase offset, it is irrelevant to the overall functionality of the chip. If the amplitude of the fields coupled into the two output waveguides of the ATEC are $a$ and $b$, the power coupled back by the Sagnac loop to the lensed fiber or RSOA is $|a|^2|b|^2$ irrespectively of the relative phase of these two coefficients and is maximized for balanced output powers. This assumes that the loop itself is lossless. In practice, the insertion losses (ILs) of the Vernier structure have to be added to the overall loss budget.

Prior to conducting experiments with the RSOA, as reported in Section III, the PIC is characterized using a lensed fiber also at its input interface. Corresponding simulations and measurements are shown in Figs. 4 and 5. Simulated ILs are shown for different lensed fiber positions, with displacements in the xy-plane parallel to the facet of the chip assuming the input coupler to be the ATEC, Fig. 4(a), or a standard edge coupler (SEC), Fig. 4(c). The latter was assumed to be formed by tapering down a 600 nm wide waveguide to a 200 nm tip width, as this was simulated to give the best insertion efficiency with the utilized lensed fiber. The length of the inverse taper was assumed to be 25 μm. The $-1 \text{ dB}$ and $-3 \text{ dB}$ alignment tolerances of the ATEC are respectively 4 and 3 times better than that of the SEC along the x-direction, as also seen in Fig. 5(c). These are defined as the range of allowable displacements to maintain the ILs within 1 dB or 3 dB of their optimum (i.e., for the ATEC the reference is conservatively taken at $x = \pm 1.7 \text{ μm}$). They are $\pm 0.6 \text{ μm}$ (SEC, $-1 \text{ dB}$), $\pm 2.4 \text{ μm}$ (ATEC, $-1 \text{ dB}$), $\pm 1.1 \text{ μm}$ (SEC, $-3 \text{ dB}$) and $\pm 2.9 \text{ μm}$ (ATEC, $-3 \text{ dB}$). However, there is also a 1-dB penalty in the peak coupling efficiency of the ATEC ($-2.8 \text{ dB} \text{ vs. } -1.8 \text{ dB}$) resulting from the multiple transitions in the structure. It should be noted though that in a conventional ECL PIC consisting in a SEC following by a separate 1-by-2 splitter, the latter would
also result in some amount of additional ILs. It may also be possible to reduce the excess losses of the ATEC associated to these internal transitions by utilizing partial etches to make them less abrupt, as previously done in silicon based structures [12].

In the vertical y-direction, the ATEC does not improve the alignment tolerance, since in both cases it results from overlap integrals between field profiles with close to matched MFD. The modeled –3 dB alignment tolerance is actually slightly worse for the ATEC (±0.7 μm vs. ±1 μm for the SEC), as a consequence of it being referenced to the IL optimum at x = ±1.7 μm but being taken along the x = 0 μm axis. This is however acceptable for the application pursued here, as the ATEC is meant to facilitate flip-chip integration for which the accuracy in x and z is determined by the placement accuracy, but the vertical alignment is defined by mechanical contacts, for example between the III-V chip and pedestals formed in a common substrate [11] or in the PIC [24].

In the z-direction, the other direction in the plane of the chips, there is also a significant improvement in alignment tolerance, as seen in Fig 4(d). In order to maintain the ILs within 3 dB of their optimum, the beam waist of the lensed fiber emission can be in a range between 0 μm to 3 μm from the edge of the PIC for the SEC. For the ATEC, this range is increased to 0 μm –7.1 μm. This is due to the supermodes of the coupled waveguide tips having a much wider width than the SEC mode, resulting in reduced diffraction (considering the reciprocal coupling problem). Thus, the ATEC provides relaxed and acceptable alignment tolerances in both in-plane directions compared to the capabilities of off-the-shelf pick-and-place processes, as the overall required alignment accuracy of ±3 μm is well in range of post-cure placement accuracies. These simulation results are summarized in Table I and compared to the experimental results described below.

![Fig. 4. Alignment dependent ILs for the ATEC and the SEC. Simulated alignment dependent losses for (a) the ATEC (sum over both waveguides) and (c) the SEC for displacements in the xy plane parallel to the facet of the chip. (b) Experimentally recorded alignment sensitivity of the ATEC for comparison with (a). (d) Simulated ILs for axial displacements along the z-direction (for centered xy alignment). All simulations were run using a Gaussian beam with an MFD of 2.5 μm matched to the MFD of the lensed fiber with which the measurements were done. The PIC-to-fiber output edge coupler losses were normalized out, as they are not part of the device characteristics.](image-url)

### Table I

|                  | IL in x | 1-dB Tol. in x | 3-dB Tol. in x | 3-dB Tol. in y | 3-dB Tol. in z |
|------------------|---------|----------------|----------------|----------------|----------------|
| SEC simulated    | 1.8 dB  | ±0.6 μm        | ±1 μm          | ±1 μm          | 0-3 μm         |
| ATEC simulated   | 2.8 dB  | ±2.4 μm        | ±2.9 μm        | ±0.7 μm        | 0-7.1 μm       |
| ATEC measured    | 2.9 dB  | ±2.6 μm        | ±3.3 μm        | ±1.05 μm       |                |

Measurements of the xy-alignment dependent ATEC ILs, corresponding to the summed power over both output waveguides, are shown in Fig. 4(b) for comparison with simulations [Fig. 4(a)]. Measurements for each of the two output waveguides reported separately are also shown in Fig. 5(a), showing that balanced output powers are maintained for displacements along the x-direction. Losses occurring at the output of the PIC, at the interface to the lensed fibers picking up the transmitted signal, are normalized out as they are extrinsic to the device. The best coupling efficiency that was measured is –2.9 dB, very close to the simulated number. There is, however, a slight imbalance between the two outputs, which is attributed to a small deviation of the interference section length from the quadrature condition. We also observe a slight asymmetry in the alignment dependent data, i.e., moving from –x to +x does not result in exactly permuting the waveguide dependent ILs. This could be attributed to a small deviation in the incidence angle of the input light beam (with respect to the z-axis) from the designed for angle, as a consequence of experimental conditions in the test setup holding the input lensed fiber. This is illustrated by a simulation with an input angle offset by 5° from nominal [Fig. 5(b)]. For comparison, the nominal case is also shown in Fig. 5(c). In this case, the two outputs are perfectly symmetric and equal for all x-displacement values.

The experimentally measured ATEC alignment tolerance is very close to the simulated one in the x-direction (see Table I). There is a moderate discrepancy in the y-direction, perpendicular to the surface of the chip, that might be due to a reduced y-axis field confinement in the experimental device, possibly due to a fabrication bias having yielded smaller than expected tip widths, or to a larger than expected lensed fiber to PIC interface distance in the experiments and some diffraction of the free-space beam.

### B. Vernier Structure

The use of a single or of multiple ring resonators is a common practice in integrated ECL design for providing wavelength selectivity. Ring resonators can be interposed in the optical path between the chip interface and a reflective element [11], used directly as a wavelength selective reflector [19], or as part of a Sagnac loop [1], [7]–[10]. The use of multiple rings in Vernier configuration for wideband laser tuning [1], [7], [11] was also demonstrated for other wavelength ranges, e.g., in the O-band [8].

For the ECL at hand, a Vernier structure consisting of two rings is implemented, that are each individually tunable with thermal tuners over an entire free spectral range (FSR) with an 80 mA current range and below 200 mW of dissipated power.
per ring. Due to the low loss of the SiN waveguide platform, it is possible to design ring resonators with very high quality (Q)-factors. On the other hand, the bending radii (and accordingly, the radius of the ring resonators) must remain larger, in comparison to Si, due to the reduced index contrast between SiN and SiO$_2$. This, in turn, leads to a small FSR, which can impair the functionality of the ECL by causing mode hopping since a large number of resonances then fall within the gain bandwidth of the RSOA if a single ring is used.

Two ECL designs were implemented on chip with different ring Q-factors, as determined by the coupling strengths to the bus waveguides. For each ECL design, two rings with the same loaded Q-factor and slightly different radii of 115 $\mu$m and 117 $\mu$m are used.

The high Q-factor effectively creates a long cavity length and therefore removes the need to use long delay lines to reduce the phase noise and the linewidth. The effective length of a ring at resonance, $L_{eff}$, can be estimated as

$$L_{eff} = \frac{2Q_Lc_0}{\omega n_g}$$

(1)

where $Q_L$ is the loaded quality factor, $c_0$ the speed of light in vacuum, $\omega$ the angular resonance frequency, and $n_g$ the group index. However, as the targeted Q-factor is increased and the coupling strengths consequently reduced, the ILs resulting from waveguide and excess junction losses inside the rings also go up. The two designs are summarized in Table II, with Design 1 being more aggressively optimized towards large Q-factors and Design 2 providing a fallback with somewhat lower losses and lower Q-factors facilitating tuning and robustness against technical noise. We fitted waveguide losses of 0.29 dB/cm from the experimentally recorded ring transfer functions, close but still above the $\sim$0.1 dB/cm expected from the PIC platform. It should however be noted that the fitted waveguide losses also include excess coupler losses that may occur at the ring to waveguide junctions.

The effective FSR of the Vernier structure can be roughly estimated as [25]

$$FSR'_V = \frac{FSR_1 \cdot FSR_2}{FSR_1 - FSR_2}$$

(2)

with $FSR_1$ and $FSR_2$ the FSRs of the two rings equal to 1.6 nm and 1.62 nm, resulting in an effective FSR of 130 nm larger than the gain bandwidth of the utilized RSOAs (see Section III).

To test the Vernier structure of Design 2, the heaters of the two rings are set to obtain overlapping resonances at 1560 nm. Light is coupled from the lensed fiber to the ATEC and the back-reflection recorded by means of a circulator. The resulting reflection spectrum is shown in Fig. 6. The peak value at $-8$ dB fiber-to-fiber back-reflection is well in line with expectations based on device characteristics for Design 2. This data also serves to verify the selectivity of the back-reflector. A single resonance remains in the range of 1500 nm to 1640 nm accessible by our test equipment, with all other resonances staying suppressed. Moreover, an off-resonance extinction ratio of $>10$ dB is obtained over the entire recorded spectrum. As seen...
TABLE III
RSOA CHARACTERISTICS

|                      | C-Band RSOA | L-Band RSOA |
|----------------------|-------------|-------------|
| Center Wavelength    | 1518 nm     | 1572 nm     |
| Vertical FWHM        | 28.1°       | 28.5°       |
| Lateral FWHM         | 15.7°       | 14.0°       |
| Current to reach transparency | 60 mA        | 60 mA       |
| Bandwidth (3dB) at 300 mA | 97.5 nm     | 96.5 nm     |
| Back Facet reflectivity | 90%         | 90%         |
| Front Facet reflectivity | < 0.01%     | < 0.01%     |
| Saturation power at 300 mA | ~60 mW      | ~60 mW      |

in the recorded spectra, displacement of the lensed fiber within the investigated range of ±3 μm along the x-direction reduces the reflection to −10.5 dB, in line with additional coupling losses as reported in Section II-A. The absence of additional excess losses provides confirmation that the functionality of the Sagnac loop is maintained.

III. EXTERNAL CAVITY LASER

After characterizing the PIC, the lensed fiber was replaced by an RSOA and a series of experiments were performed to characterize the ECL. We use commercial RSOAs operating in the C- and L-bands. As already mentioned in the introduction, experiments were performed here by aligning the RSOA with computer controlled opto-mechanics, allowing investigation of alignment tolerances in the complete ECL system. Fig. 2 shows the corresponding setup. The ceramic RSOA submount is directly attached to a copper heatsink with thermally conductive glue, without interposing a thermo-electric cooler. Fanout of the RSOA contacts to a printed circuit board via wire-bonds facilitates connectivity in the setup. The PIC is directly contacted with probe tips.

The main specifications of the RSOAs are summarized in Table III. The light beam exits the RSOA with a nominal angle of 19.5° relative to the surface normal of the output facet, in order to reduce internal reflections. The back-facet of the RSOA has been provided with a high-reflectivity coating, while the front-facet is antireflection coated.

Lasing spectra were recorded for both Vernier structure designs, we shall however focus first on Design 1 to introduce the general laser characteristics such as single mode operation and LI-curve, that did not depend much on which of the PIC designs was used. The experimental characterization of alignment tolerances and Lorentzian linewidths later on in this section contain a detailed comparison between ECLs operated with the two PIC designs, as internal losses and delayed feedback were expected to play a substantial role there. Wideband tunability of the laser was shown with Design 2, as the reduced Q-factors facilitated tuning and laser stability in an opto-mechanics based setup.

An example of the recorded optical spectrum, for a high Q-factor Design 1 device operated with the C-band RSOA and an injection current of 200 mA, is shown in Fig. 7(a). The side-mode suppression ratio is above 73 dB at 1548 nm with the measurement limited by the noise floor of the spectrum analyzer.

To confirm single mode operation, the spectrum was recorded over the entire range of the high-resolution optical spectrum analyzer (1520 nm to 1629 nm) and this was the only laser mode that was found. Fig. 7(b) shows the optical power versus applied RSOA current (LI-curve) with the Vernier structure tuned to 1530 nm, close to the gain maximum of the RSOA. The onset of lasing is at an RSOA injection current of 70 mA, just slightly above the 60 mA required to obtain positive gain (Table III). Power levels reported in this section [Figs. 7(b) and 8(a)-(d)] correspond to the power coupled to a lensed fiber at one of the output ports of the PIC (Out 1). Recorded power levels of ~1 mW are in the expected range, given the ~60 mW saturation power of the RSOA, the 3-dB losses at the RSOA-to-PIC interface, the 5-10 dB on-resonance extinction of the rings (the rest is being coupled back), the 3-dB PIC-to-fiber outcoupling efficiency of

Fig. 7. (a) Laser spectrum for Design 1 operated with the C-band RSOA and an injection current of 200 mA, recorded with a resolution bandwidth (RBW) of 5 MHz. Power is indicated in dBm, since the entire laser line falls within the RBW and recorded power levels are directly plotted instead of being divided by it. (b) Laser output as a function of current with the Vernier structure tuned to 1530 nm. The threshold current is 70 mA.

Fig. 8. Laser output power for both PIC designs and for misalignments in the x- and y-directions. Output power as a function of (a), (c) x-axis alignment and (b), (d) y-alignment, respectively for Design 1 (a), (b) and Design 2 (c), (d). For Design 1, the PIC was operated with the C-band SOA with an injection current of 275 mA. The Vernier structure was tuned to 1530 nm. For Design 2, the PIC was operated with the L-band SOA with an injection current of 200 mA. The Vernier structure was tuned to 1605 nm. In all panels, dashed lines indicate the range in which lasing occurs, marked by a sharp increase in the output power.
the SECs (that is experimentally slightly worse than simulated values), and the power being split over the two output waveguides.

The alignment tolerance between RSOA and PIC was tested by moving the RSOA along the x- and y-directions parallel to the chip facet, with the Vernier structure on the PIC tuned to a given wavelength. The system’s output power for Design 1 operated with the C-band SOA, as above, a 275 mA injection current and the Vernier structure tuned to 1530 nm is shown in Fig. 8(a). Lasing was obtained in a range of lateral displacements of ±5 μm, with boundaries shown by dashed lines in the figure. At the edges of this misalignment range, the output power sharply drops as the losses become larger than the small signal gain of the RSOA, lasing action ceases, and only amplified spontaneous emission (ASE) remains. Within the ±5 μm misalignment range, the characteristic shape of the ATEC can be recognized. However, the dependency of the laser output power on misalignment is much more pronounced than the misalignment dependent ILs recorded during the passive characterization measurements (compare to Fig. 5).

This is a consequence of the laser output power depending nonlinearly on internal cavity losses close to threshold. This can be exemplified by describing the RSOA gain saturation with a simple model as \( G = G_0/(1 + P_{in}/P_{sat,in}) \), with \( G_0 \) the small signal (round-trip) gain, \( P_{in} \) the power at the input of the RSOA and \( P_{sat,in} \) its 3-dB gain compression input saturation power. This results in \( P_{in} = (G_0 R - 1) P_{sat,in} \) with \( R \) the (power) reflection coefficient of the PIC and \( P_{out} = (G_0 R - 1) P_{sat,in}/R \), with \( P_{out} \) the power at the output of the RSOA. The power coupled to the PIC thus scales as \( T (G_0 R - 1) P_{sat,in}/R \), with \( T \) the power coupling coefficient between the RSOA and the PIC. In the limit where \( G_0 R \gg 1 \), the laser output power is simply \( T G_0 P_{sat,in} \) and scales with the ILs of the ATEC. However, as \( G_0 R \) approaches 1, \( T (G_0 R - 1) P_{sat,in}/R \) depends strongly on \( R \), that in turn scales as \( T^2 \). Below threshold, coherent emission collapses and the RSOA only emits ASE. The power generated by the device then also scales simply as \( T \), albeit with a much lower proportionality factor.

As mentioned earlier, a comparison between the alignment tolerances as obtained for the two chip designs is now of interest. Fig. 8(c) shows a second measurement done for a Design 2 device operated with the L-band RSOA, an injection current of 200 mA, and the Vernier structure tuned to 1605 nm. Compared to the Design 1 chip used above, Design 2 has rings with lower loaded Q-factors (215000 vs. 600000), but also lower ILs per ring (1 dB vs. 2 dB), reducing the round trip losses and thus facilitating maintaining laser action over a wider misalignment range. In line with this, the ECL was found to lase in a slightly wider range of lateral displacements covering ±6 μm. Also, the laser emission as a function of lateral displacements can be seen to be much more flattop in this dataset. There are however further experimental factors playing a role here:

The overall reduction of the sensitivity towards misalignment induced ILs is seen even though the injection current here was lower and the small signal gain thus presumably reduced (the RSOAs have very similar properties other than their shifted emission spectra), partially offsetting the reduced ILs. On the other hand, for the previous dataset shown in Fig. 8(a), the RSOA remained at a significant distance, larger than 10 μm, from the PIC, as opposed to Fig. 8(c), for which the laser to PIC distance was more aggressively optimized (accepting the risk of potentially crashing the RSOA in the utilized setup), which may also have contributed to further improvement of the round trip losses. Further aspects such as small errors in angular alignment or a slight error in the length of the interference section in the different devices leading to a small offset from the quadrature condition may have further played a role. These should however be straightforwardly addressed in a production environment in which placement accuracies much better than the 5° angular offset assumed in Fig. 5(b) as well as reproducible fabrication of optimized devices would be achievable (see below for an analysis of required fabrication tolerances).

Lastly, the ECL described here does not have a separate phase shifter to align the Fabry-Perot resonances resulting from the overall cavity formed by the RSOA and the PIC with the resonances of the rings. Given the 1 mm RSOA length and the equivalent delay lengths of the rings, we estimate the FSR of the Fabry-Perot resonances to be 0.52 GHz for Design 1 and 1.4 GHz for Design 2. The full width at half maximum (FWHM) of the rings, on the other hand, are 0.32 GHz and 0.9 GHz, and are below the corresponding Fabry-Perot FSR, so that there is no guarantee for Fabry-Perot resonances to be centrally located in the Vernier resonance. Given that moving to the edge of the FWHM results in a 3-dB drop in input to drop port coupling efficiency per ring (i.e., 6 dB total), it can be seen that there can be a significant spread in internal laser cavity losses between experiments, as well as outcoupling coefficients, potentially leading to some spread in the recorded data. While this did not appear to be a predominant problem, as stable lasing was obtained once the ring resonances were tuned to coincide, irrespectively of e.g., small variations in the RSOA to PIC distance influencing the spectral positions of Fabry-Perot resonances, some irregularities are seen in the LI curves [Fig. 7(b)] that may be associated to this. Given the relatively high Q-factor of the utilized rings, frequency pulling might have also played a role in facilitating alignment of the laser wavelength with the ring resonances [26, 27].

In addition to the sensitivity of the laser to x-direction misalignment, we also investigated the effect of misalignment in the y-direction, vertical to the chip surface [Figs. 8(b) and 8(d)]. Here, the ECL using the higher loss / higher-Q chip corresponding to Design 1 featured the better alignment tolerance of ±3.5 μm, vs. ±2.5 μm for Design 2. This further points at the various experimental uncertainties playing a role here. Since both the RSOA and ATEC modes have wider diffraction angles in the y-direction, the alignment tolerances measured here are particularly sensitive to the RSOA to PIC distance.

Finally, the reader may notice that the maximum output power recorded for Design 2, Figs. 8(c), 8(d), is lower than for Design 1, Figs. 8(a), 8(b). This is a consequence of both the reduced injection current and of the outcoupling coefficient of Design 2 (power coupled from the output waveguides of the ATEC to ports Out1 and Out2 in Fig. 1) being reduced from 30% to 10% (see Table II) as a consequence of the choice of waveguide-to-ring coupling coefficients.

The next set of experiments aimed at characterizing the tunability of the ECL and were carried out with a Design 2
device and the C-band RSOA operated at a 200 mA injection current. For these, we focus on Design 2 due to its lower Q-factor facilitating wavelength tuning. By tuning the resonances of the two ring resonators on the PIC, a large tuning range measured to span over 100 nm was achieved, limited by the RSOA’s gain bandwidth. Fig. 9(a) shows the whole tuning range of the ECL (just selected lines are shown for clarity, so that the output power levels can be seen). By tuning one of the ring resonators while keeping the current applied to the thermal tuner of the second ring constant, it is possible to hop from one ring resonance to the next and thus change the lasing wavelength by one ring FSR [Fig. 9(b)]. Furthermore, it is possible to tune the lasing wavelength within a single FSR of an individual ring resonator by changing the current applied to both rings [Fig. 9(c)].

The range of achievable lasing wavelengths is expected to be limited primarily by the gain spectrum of the RSOA, with the bandwidth of the ATEC playing a secondary role. Simulations show that an ATEC with an interference section length optimized to obtain the targeted quadrature condition and thus balanced waveguide output power levels at 1550 nm reaches an output imbalance of 3 dB at 1500 nm and 1600 nm. For this level of imbalancing, the reflection of the Sagnac loop into the RSOA mode, \( |\alpha|^2 \) as discussed above, drops by only 0.5 dB. Moreover, the bandwidth of the ATEC can be improved by reducing its length [12], which ought to be possible here as the adiabatic transitions have been conservatively designed.

We also assessed the tolerance of the ATEC to manufacturing tolerances and found that increasing the width of all features by 20 nm over its entire length resulted in an imbalance of 4 dB, corresponding in the reflection dropping by 0.9 dB.

Finally, the linewidth of the ECLs was estimated using the delayed self-heterodyne (DSH) measurement technique using a 6.5 km fiber delay. We used the model from [28] with a Voigt fit to extract a Lorentzian linewidth. Design 1 and Design 2, both operated with the L-band SOA at an injection current of 200 mA, feature very similar performance. Design 1, with the Vernier structure tuned to 1584 nm, features a Lorentzian linewidth of 42 kHz and a 1.2 MHz Gaussian component. Design 2, with the Vernier structure tuned to 1617 nm, features a Lorentzian linewidth of 39 kHz and a 139 kHz Gaussian component, with the recorded spectrum and the corresponding fit shown in Fig. 10. The increased Gaussian component of Design 1 might be caused by the larger Q-factors making stabilization of the system harder and increasing the sensitivity to technical noise induced by environmental conditions. Surprisingly, the Lorentzian component of Design 1 is not better than that of
Design 2 even though the ring Q-factors and thus the round trip time delay have been significantly increased, while the ring induced losses only went up marginally.

Minimization of optical losses in the extended laser cavity, as limited in particular by the PIC-to-RSOA insertion losses, are essential to obtain low laser linewidths [21] and high wall plug efficiencies. Very low Pic-to-RSOA losses of 1.55 dB have been obtained with a silicon-on-insulator (SOI) PIC platform with inverse tapers tapered down to a very low 50 nm width and overlaid with silicon oxy-nitride (SiON) in order to obtain the required mode profiles [29]. More recently, similar performance (1.6 dB) has been obtained with SiN PICs, in which a taper width of 450 nm proved sufficiently small to obtain the required mode sizes owing to the reduced index contrast and the 200 nm thick waveguides [30] (as opposed to the 800 nm film thickness used here).

Another strategy to couple light between devices in multi-chip assemblies consists in polymer based photonic wire-bonds, that can be defined and 3D printed after the chips have been permanently attached [31]. This technique has also been recently applied to ECLs, with 2.1 dB insertion losses reported between the PIC and RSOA [32]. Both photonic wire-bonds and the multi-mode, alignment tolerant edge coupler used here present the advantage that chip mounting tolerances can be significantly relaxed. In the first case, misalignment can be corrected post-mount by the exact routing of the wire-bond, in the second case by not forcing the light to transit through a single-mode funnel at the interface between the chips, leveraging all the degrees of freedom afforded by the Sagnac loop configuration with two coupled-to-waveguides. Our approach presents the advantage of not requiring post-mount analysis and further processing after chip assembly, however some additional progress remains to be made for it to also meet the best reported insertion losses at nominal alignment. The current insertion losses of almost 3 dB still suffer from some mode mismatch at the onset of the array of tips, whose supermodes only imperfectly emulate the targeted expanded slab modes. Further engineering of this interface, for example with more freedom in regard to film thickness and critical dimensions, might allow to improve further on these results.

IV. Conclusion

In this work, we demonstrated an ECL with an alignment tolerant interface between the gain chip and the PIC. It allows for easier coupling and promises higher yield in high volume manufacturing. The alignment tolerance of the alignment tolerant edge coupler is three times better than that of a standard edge coupler in the x-direction, parallel to the edge of the chip, and improved by over a factor 2X in the axial z-direction, away from the edge of the chip. High confinement silicon nitride waveguides, with low loss and medium mode confinement, allow for maintaining a compact ECL size. At the same time, it is possible to achieve very good results in terms of tunability, output power, and linewidth.

Summarizing the characteristics for Design 2, lasing was maintained for x-axis displacements in a range of ±6 μm. Operated with a single C-band RSOA, the laser can be tuned in a range exceeding 100 nm, from 1488 nm to 1593 nm, limited by the gain bandwidth of the RSOA. A Lorentzian linewidth of 39 kHz was measured. Ongoing work aims at further reducing this linewidth by improving insertion losses and using antireflection coatings to further reduce parasitic effects.

The main challenges seen while using the alignment tolerant couplers in a laboratory environment were proper angular alignment between the two chips and meeting the required quadrature condition inside the alignment tolerant edge coupler that ensures maximum alignment tolerance. These challenges should be overcome with controlled, automated assembly in a manufacturing environment.

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