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Monolithically integrated InP-based DBR lasers with an intra-cavity ring resonator

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Abstract: We investigate the effect of a ring resonator on the linewidth and output spectrum of monolithically integrated extended cavity multi-section DBR lasers with an intra-cavity ring resonator. The goal is to achieve an understanding of whether and how the use of an additional ring filter improves the performance of a DBR laser on the aspects of the SMSR and intrinsic linewidth using the capabilities of the InP active-passive integration platform. The laser output spectrum is in good agreement with our theoretical calculations from a steady-state spectral model. A side-mode suppression ratio between 60 and 70dB is measured for a range of operating semiconductor optical amplifier currents. The frequency noise power spectral density is measured for a range of output power levels. A minimum intrinsic linewidth of 63 kHz is reported. We compare the measured Lorentzian linewidths with our theoretical expectations and present estimates of the possible linewidth improvement with the available photonic integration technology used in this work.

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1. Introduction

In recent years semiconductor continuous wave (CW) narrow linewidth lasers have become increasingly important. They are enabling devices in numerous fields including telecommunications and use of high order modulation formats for high spectral efficiency [1], RF signal generation for radio over-fibre distribution and wireless communications [2,3], light detection and ranging (LIDAR) [4] and quantum optics [5]. Furthermore they are utilized in metrology and sensing of strain, pressure and temperature applications [6,7] where low linewidth enables higher resolution.

The linewidth of a laser is the result of two dominant contributions. These are the amplified spontaneous emission (ASE) which defines the intrinsic linewidth and technical noise in the form of 1/f which is dominating at lower frequencies. The effect of the ASE on the linewidth of a single frequency semiconductor laser can be described by the Schawlow-Townes-Henry formula [8,9]. This theory states that the linewidth of a laser due to ASE is proportional to the optical losses per unit length inside the laser cavity. It is therefore necessary to keep all intra-cavity losses such as scattering due to roughness, material absorption, spectral filters and out-coupling from the cavity also minimal. Furthermore longer lengths of low loss waveguide in the cavity reduce the loss per unit length thus improving the linewidth. For example, semiconductor optical amplifiers (SOA) typically have a high internal optical loss per unit length [10] compared to passive waveguides. Extended cavity lasers which include a long low loss passive waveguide (usually of different material) significantly reduce the average loss per unit length and obtain a significantly lower intrinsic linewidth [11]. Increase of the cavity length however does not further reduce the linewidth if the length exceeds the inverse of the passive waveguide loss [12]. Increasing the cavity length however also reduces the cavity mode spacing and consequently the modes undergo similar round trip gain thus increasing mode competition. In this case,
additional filters in the cavity may be necessary to ensure single mode operation of the laser with a sufficiently good side-mode suppression ratio (SMSR).

Different integration technologies, material systems and design strategies have been used to realize single mode lasers and improve their linewidth. Excellent results, with sub-kHz intrinsic linewidths, below 300 Hz and 60 dB SMSR have been demonstrated by an extended cavity laser containing ring resonators using the hybrid integration of silicon nitride and InP gain element [13]. Extended cavity lasers with multiple intra-cavity ring resonators and 500 Hz and 2.5 kHz intrinsic linewidth were reported using heterogeneous integration of III-V bonded on silicon [14,15]. The SMSR in [14] reached 60 dB. Other examples of heterogeneous integration include engineering of the transverse mode overlap with the III-V material by using an oxide layer in-between that and Si have been reported with 1 kHz intrinsic linewidth [16] and SMSR of 55 dB. In the last few years monolithically integrated distributed Bragg reflector (DBR) lasers have also made considerable advances. In [17] DBR lasers with sampled gratings with lowest linewidth of ∼45 kHz and 57 dB SMSR are demonstrated. The lasers however include a booster SOA and an additional spectral filter at the output of the cavity to improve the SMSR. In [18] DBR lasers with supermode DBRs and InGaAlAs multi-quantum well material show linewidth of ∼55 kHz and SMSR of 56 dB. The lowest intrinsic linewidth results have been obtained using cavities with several intra-cavity ring filters in hybrid and heterogeneous integration technologies.

In this paper we are investigating the use of an intra-cavity ring filter to improve the spectral output of laser realized in a monolithic photonic integration platform. We achieve this without significantly increasing the laser footprint. We present the design, experimental results and analysis of the spectral output and frequency noise power spectral density of monolithically integrated extended cavity lasers with two DBR sections and a single intra-cavity ring resonator. Three lasers with different combinations of SOA and DBR lengths are designed and fabricated in a commercially available InP-based active-passive generic integration technology [19,20] by making use of a standardized available component library.

This paper is organized as follows. In section 2, we present details on the cavity design and the design considerations. This design aims to further suppress all unwanted cavity modes further than the DBR mirrors do. In section 3 the results of a compact steady-state spectral model and a comparison with a multi-section DBR laser are presented. In section 4, the experimental results on the current-light-voltage curves are presented and the spectral quality is compared with the model. The power spectral density of the frequency noise and linewidth performance of three fabricated lasers with different lengths of SOAs and DBR mirrors are presented. In section 5 we discuss the findings of the linewidth characterization and compare them to our theoretical calculations. We discuss possible increase of the effective length of the ring resonator and subsequent improvement of the linewidth based on the existing technology. We end the paper with summarizing the main conclusions.

2. Laser cavity

In order to reduce the intrinsic linewidth of an integrated laser one can increase the cavity length of a laser [12]. There are two ways to achieve this. The first one is to increase the physical length of the cavity by adding more low loss passive waveguide, as done with external cavity lasers for example. The implications of this lengthening on its single mode operation, as already mentioned in the introduction, are however that it is increasingly difficult to obtain single longitudinal mode operation. Here, we focus on the second way to increase the cavity length by increasing the effective length [21] instead of the physical one. To achieve an effective length increase, typically ring resonators are placed into the laser cavity. The complex electric field transmitted through a
ring cavity filter $E_i$ is given by [22]

$$E_i = -\kappa_1^*\kappa_2\sqrt{a_1e^{\theta}}\frac{\sqrt{\alpha e^{\theta}}E_i}{1 - t_1^*t_2\alpha e^{\theta}E_i},$$

(1)

where $E_i$ is the input field amplitude $\kappa_{1,2}$ and $t_{1,2}$ are the electric field coupling and self-coupling coefficients of the two coupling regions respectively, $\alpha_r$ is the round trip transmission coefficient and $\theta = \beta L$ where $\beta$ is the propagation constant of guided light and $L$ is the ring circumference. The * denotes the conjugated complex. The effective length of a ring resonator $L_{eff}$ can be calculated by

$$L_{eff} = \frac{\lambda}{\beta} \left( \frac{d\varphi}{d\lambda} \right),$$

(2)

where $\varphi = \arg(E_i)$ is the effective phase delay and $\lambda$ the vacuum wavelength. The steeper the slope $d\varphi/d\lambda$ of the phase delay is around the resonant wavelength, the longer is the effective length $L_{eff}$ of the resonator. To obtain a longer effective length from a ring resonator the round trip losses need to be minimized and therefore the power coupling to the ring must be low as well. Examples of this approach are lasers in [13–15,23] where high-Q resonators are used in order to increase the effective length and furthermore for tuning purposes.

In a similar way, we add an intra-cavity ring resonator in a multi-section DBR laser to investigate the effect on the linewidth and output spectrum of the laser. A schematic of the laser cavity is shown in Fig. 1(a). The cavity is formed by the two DBRs and it includes a SOA, a ring resonator and passive waveguides that connect all the components. The DBR grating design has a 50% duty cycle, a designed coupling coefficient of 50 cm$^{-1}$ and the rear and front gratings are 400 and 300 $\mu$m long respectively. For these lengths, the reflectivities are predicted to be 85% and 70% respectively. The rear DBR length was chosen close to the maximum length available for the fabrication service. The length choice of the front DBR is a compromise between the output power and linewidth since higher reflectivity mirrors theoretically result in lower linewidth but also lower output power. The SOA length is 500 $\mu$m long and it contains four quantum-wells. The SOA is based on shallow etched ridge waveguide and provides higher gain for the transverse-electric (TE) polarization mode. A cross-section of the SOA is shown in Fig. 1(b). Above and below the multi-quantum-well (MQW) material there is quaternary material with bandgap at 1.25 $\mu$m (Q1.25). The substrate and cladding are n-doped and p-doped InP material with gradient doping (the dark blue color represents heavier doping than the lighter blue). The ring resonator is formed by two $2 \times 1$ multimode interference (MMI) couplers. The MMIs couplers are also used to couple light in and out of the ring resonator. The power splitting ratio of the MMIs is 50% and their expected excess insertion is less than 1 dB.

In the design procedure, we minimized both the circumference of the ring resonator and the cavity length in order to keep the free spectral range (FSR) of the ring and cavity mode spacing as large as possible. E.g. let’s assume the ring resonator resonance is in the centre of the DBR stop-band. If the ring resonator FSR is equal or larger than half the DBR stop-band width, every other cavity mode within the DBR band will be suppressed by the ring filter. The $2 \times 1$ MMIs were chosen instead of $2 \times 2$ MMIs that are also available in this technology because they are shorter. The arc radius of the ring resonator is 80 $\mu$m which is about the minimum with low bending losses ($\sim 0.1$ dB per 90°). The result is a ring with 1.02 nm (128 GHz) FSR and a laser cavity mode spacing of approximately 0.10 nm (12.5 GHz). The stopband width of the DBR mirrors is approximately 2 nm (250 GHz) which means that the first cavity modes that fall within the ring resonator transmission are at the edge of the band thus should be greatly suppressed. A larger ring radius would mean that more ring modes would exist within the DBR stopband and cavity modes would be present in the transmission resonances. Therefore these cavity modes would not be further suppressed by the ring resonator but only by the DBR mirror.
Fig. 1. (a) Schematic of the DBR laser with an intra-cavity ring resonator. The DBR mirrors that form the cavity are 300 µm and 400 µm long and the SOA 500 µm. The coupling to the ring resonator is implemented using 2 × 1 MMIs. (b) Cross-section of the SOA with the active core containing 4 quantum-wells, placed between Q1.25 quaternary material and n- and p-doped substrate and cladding respectively.

3. Compact steady state spectral model

A phenomenological steady state spectral model [24] was developed in order to estimate the output spectrum of the laser. Using this model, we calculated the output spectrum of the laser very close to threshold. The model is based on a transfer matrix (T-matrix) formulation [25]. The electric field amplitude and phase transmission response of every element in the cavity (SOA, ring resonator, passive waveguide, DBR mirrors) is described by a wavelength dependent T-matrix (Fig. 2(a)) and all of them can be lumped to a single matrix, $T_{\text{intra-cavity}}$ in Fig. 2. The T-matrix for length $L$ of passive waveguide is

$$
T_{\text{passive-wg}} = \begin{bmatrix}
e^{-j\frac{2\pi}{\lambda} n_{\text{eff}} L e^{a_{\text{passive}} L}} & 0 \\
0 & e^{j\frac{2\pi}{\lambda} n_{\text{eff}} L e^{-a_{\text{passive}} L}}
\end{bmatrix},
$$

(3)

where $a_{\text{passive}}$ is the passive loss per unit length and $n_{\text{eff}}$ the effective index of the propagating mode. The two exponential terms represent the phase accumulation and propagation loss of the propagating electric field. The anti-diagonal elements are zero, indicating that no reflections or backscattering is assumed. If the passive loss $a_{\text{passive}}$ in Eq. (3) is substituted by the modal gain of the SOA, the matrix becomes the SOA T-matrix. The ring resonator T-matrix is

$$
T_{\text{ring}} = \begin{bmatrix}E_i/E_t & 0 \\
0 & -E_i/E_t
\end{bmatrix},
$$

(4)

where $E_i$ is the electric field transmission through the ring resonator as defined in Eq. (1).

The total amplitude and phase response of the DBR mirrors are also calculated by multiplying T-matrices describing the short waveguide sections with higher and lower refractive index and the reflections at their interfaces. By using the T-matrix definition equations and adding the amplified spontaneous emission (Fig. 2(b)) the following equation system is obtained

$$
A_1 = A_2 T_{11} + B_2 T_{12} + ASE,
$$

(5)

$$
B_1 = A_2 T_{21} + B_2 T_{22},
$$

(6)

where ASE is the amplified spontaneous emission, $T_{11}$, $T_{12}$, $T_{21}$ and $T_{22}$ are the corresponding elements from the total T-matrix of all intra-cavity elements. We consider no intra-cavity
Fig. 2. (a) In the red dashed rectangle, the individual elements inside the cavity are presented. Every component is described by an individual $T$-matrix and the $T_{\text{intra-cavity}}$ that describes a single-pass transmission through all the components can be calculated by matrix multiplication. The cavity is formed by the two DBR mirrors. (b) By adding the amplified spontaneous emission (ASE) and solving the equations that describe the system with the boundary conditions (DBR reflectivities) we can calculate the electric field in the cavity.

reflections therefore $T_{21}$ and $T_{12}$ are zero. By imposing the boundary conditions (DBR mirrors) using $A_1 = B_1 R_{\text{DBBR}}$ and $B_2 = A_2 R_{\text{FDBR}}$, where $R_{\text{DBBR}}$ and $R_{\text{FDBR}}$ are the reflectivities of rear and front DBR mirrors respectively, and solving the linear equation system, the relative steady state amplitude of the envelope of a monochromatic single transverse mode is calculated by:

$$E(\lambda) = \text{ASE} \frac{T_{22} R_{\text{DBBR}}}{T_{11} - T_{22} R_{\text{DBBR}} R_{\text{FDBR}}}, \quad (7)$$

The field amplitude is calculated for a range of wavelengths for a specific SOA modal gain. The SOA gain is gradually increased until the round trip gain almost reaches unity somewhere in the wavelength range. At this point the laser almost reaches unity - threshold. The value of ASE that is used in this case is $10^{-4}$.

In Fig. 3 the calculated output spectra for the DBR laser with an intra-cavity ring resonator with the details given in section 2 (orange) and a multi-section DBR laser with 350 $\mu$m long SOA, 500 $\mu$m and 50 $\mu$m long DBR mirrors and a 300 $\mu$m long phase section (yellow) is shown.

Fig. 3. Recorded (blue) and calculated (orange) spectra for a multi-section DBR laser with an intra-cavity ring resonator and calculated spectra for a multi-section DBR laser (yellow). The blue trace is a recorded spectrum of the laser at 20 mA, slightly above threshold (res. BW 5 MHz) and it is in good agreement with the calculated spectrum for the same laser (orange). According to the calculations even though the cavity length of the DBR-RR laser is longer and the mode spacing smaller, with obtain a higher SMSR compared to a multi-section DBR laser (yellow).
Despite the longer cavity length and therefore the smaller cavity mode spacing, the DBR laser with the intra-cavity ring resonator (orange line) is expected to show a higher SMSR. This is caused by the wavelength selectivity due to the ring resonator. Even though the neighboring cavity modes are closer to the lasing mode (by almost a factor of 3) they are further suppressed compared to the shorter laser with DBRs only (yellow line).

4. Characterization results of ring resonator and laser

The DBR laser with ring resonator and a separate identical ring resonator were both characterized at 18 °C, regulated by a watercooler.

4.1. Ring resonator

The transmission of the ring resonator with 80 µm radius and 2 × 1 MMIs as described in Section 2 was characterized for TE polarized light in a circuit separate from the laser. The light was launched using a single mode polarization maintaining lensed fibre. After passing through the ring resonator, light was collected using a standard single mode lensed fibre. The facets of the chip are coated with anti-reflection coating. The ring resonator showed a quality factor \( Q = \frac{\omega}{2\pi\text{FWHM}} \) of about 5500 and a finesse \( F = \frac{\text{FSR}}{\text{FWHM}} \) of 5. By assuming the coupling coefficient to be 0.5 (MMI splitting ratio), the round-trip transmission coefficient (percentage of the transmitted power after a single round-trip in the ring resonator including coupling and propagation losses) was extracted and found to be about 0.67 at the resonance wavelength. The round-trip loss corresponds to −1.7 dB around 1540 nm. Assuming 3 dB/cm for the passive waveguides [19–20], which is also confirmed by the information supplied by the foundry, the propagation loss for the circumference of the ring is ∼0.15 dB. The bending losses which are dependent on the ring radius are approximately around 0.1 dB/90° so the total bending losses of the ring are about 0.4 dB. The remaining loss which is ∼1.15 dB is attributed to the two MMIs of the ring resonator. From the extracted parameters the effective length \( L_{\text{eff}} \) of the ring resonator was calculated to be about 0.8 mm. This is an enhancement factor of about 25% compared to the physical length.

4.2. Laser characterization

In Fig. 4(a) the voltage-current (VI) and light-current (LI) curves of the characterized laser with 500 µm SOA and 300 and 400 µm long DBRs are presented. The threshold current is 15 mA corresponding to a current density of 1.5 kA/cm². The maximum output power of the laser exceeds 5 mW at 100 mA. This power is the optical power in fibre to which we added the coupling losses from the chip facet to the lensed fibre and which are estimated at 4 dB. Above 60 mA the thermal roll-off starts to appear gradually. The series resistance calculated from the VI curve slope is about 6 Ω. A spectrum at 22 mA is shown in Fig. 3 (blue trace), recorded with a high resolution optical spectrum analyzer (APEX AP2641B) with a resolution of 5 MHz. In Fig. 3 we show that the recorded spectrum is in reasonable agreement with our compact steady-state spectral model and exhibits an SMSR of about 65 dB. Some discrepancy is observed between our model and the measured spectra with respect to the side-modes and the resulting SMSR. We attribute this discrepancy to the deviations of the fabricated components from the design values used in our simulations. Furthermore even though the ASE value used for the calculations was validated in [24], it might not be entirely accurate. The value was extracted from a different laser on a different wafer and changes in the SOA properties could arise. The neighboring cavity modes are just visible above the noise floor of the spectrum analyzer. The SMSR is maintained above 60 dB and reaching almost 70 dB for the whole current range up to 100 mA (Fig. 4(b)). The wavelength shift over the whole current range up to 100 mA is mode-hop free.
4.3. Laser frequency noise power spectral density characterization

In this subsection, we characterize the frequency noise power spectral density of three lasers with the cavity structure as the one presented in Fig. 1 and in the previous subsections. The three lasers include different SOA and DBR lengths.

An overview of the three different combinations is given in the legend of Fig. 5(b). Their frequency noise was measured using a commercial frequency noise measurement setup (OEwaves OE400). The SOA of each laser was pumped using a low-noise laser diode controller (ILX LDX-3620B) and its optical output was amplified using a low noise-figure erbium-doped fibre amplifier (Keopsys CEFA-C-HG) in order to obtain sufficient optical power for the frequency noise measurements. The ASE of the EDFA was filtered using a narrowband optical filter with 0.4 nm bandwidth. Frequency noise measurements were taken over a range of SOA current levels and different optical output power levels.

In Fig. 5(a) recorded spectra of the single-side frequency noise of the laser with an SOA length of 750 µm and front and rear DBR lengths of 300 and 400 µm, respectively, are presented. From 100 Hz frequency to 10 kHz, 1/f noise is dominant. In the range from 10 kHz to about 2 MHz, 1/f² flicker frequency noise is visible, where s < 1. The spectral density of the frequency noise becomes white (flat) approximately above 3 MHz. The level of the flat part of the single-sided frequency noise multiplied by π gives the intrinsic (Lorentzian) linewidth of the laser [26]. Multiple spurious peaks due to electromagnetic interference are visible in the spectra. The white part of the frequency noise is decreasing with increasing current from 25 to 50 mA as described by the modified Schawlow-Townes formula. It reaches its minimum spectra density of 20 Hz²/Hz at 50 mA (green trace). We chose to average the points that fall within the orange shaded range which is flat and no spurious peaks are present. The linewidth is then calculated to be 63 kHz for the measured power spectral density for the laser with 750 µm long SOA and 300 µm and 400 µm long DBR mirrors. At 100 mA SOA current the laser linewidth increases (red trace).

In Fig. 5(b) the Lorentzian linewidths of the three lasers are presented as a function of the inverse normalized optical output power. With increasing SOA current and increasing output power the Lorentzian linewidth is initially decreasing as expected for all three lasers. The
**Fig. 5.** (a) Single-side power spectral density of the frequency noise for the laser with 750 µm long SOA and 300 and 400 µm long DBR mirrors at different SOA current levels. The range indicated by the orange shaded area is the averaging region used to calculate the intrinsic laser linewidth. (b) The Lorentzian linewidth calculated from the white noise part of the frequency noise spectrum is plotted as a function of the inverse normalized output power for the three lasers. The minimum linewidth for the three lasers are 63 kHz (blue), 71 kHz (orange) and 93 kHz (yellow). A linewidth floor and a consequent linewidth increase is observed for all three lasers.

The minimum Lorentzian linewidth observed for the three lasers are 63 kHz, 71 kHz and 91 kHz. Comparing the lasers with the same SOA length (500 µm) but different DBR mirror length, we observe that the laser with longer mirrors and therefore higher reflectivities exhibits a lower linewidth (71 kHz). The lowest linewidth is observed from the laser with a longer SOA of 750 µm. In Table 1 the performance of the three lasers in terms of SMSR and intrinsic linewidth is summarized.

<table>
<thead>
<tr>
<th>SOA length (µm)</th>
<th>Rear DBR length (µm)</th>
<th>Front DBR length (µm)</th>
<th>Average SMSR (dB)</th>
<th>Min. linewidth (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>400</td>
<td>300</td>
<td>67</td>
<td>63</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>400</td>
<td>62</td>
<td>71</td>
</tr>
<tr>
<td>500</td>
<td>400</td>
<td>300</td>
<td>64</td>
<td>91</td>
</tr>
</tbody>
</table>
At higher optical output power levels the linewidth is not further decreasing as Schawlow-Townes-Henry formula describes but a linewidth floor is encountered. The linewidth floor in semiconductor lasers, both monolithically and heterogeneously integrated, has been previously observed and is a known phenomenon which however lacks a definite explanation [12]. Some possible explanations like non-uniformity of the optical power and carrier distribution along the cavity, two-photon absorption and thermal fluctuation processes have been proposed [27–28]. The current densities at which the linewidth floor occurs in this case are 5-6 kA/cm² for the short SOA lasers and 3.5-4 kA/cm² for the longer one. Since these current densities are different, they do not indicate a direct link with the linewidth floor.

If the non-uniformity of the optical power over the SOA is responsible for the increase in linewidth at higher output powers, the effect could be mitigated by the reduction of passive losses and distribution of the losses symmetrically over the two passive section on both sides of the SOA. Alternatively a segmented SOA could be used in the cavity. Another possible cause for the broadening is an increase in optical loss in the SOA at higher current levels and light intensity. Free-carrier absorption can increase as well as two-photon absorption in the amplifier. Furthermore the two-photon absorption could increase in the passive section of the lasers. The reduction of two-photon absorption would require the use of quaternary material with bandgap larger than 1.25 µm which is currently used for the wave guiding layers and above and below the active core. This would ultimately require to redesign of both the SOA and passive waveguide cross-section.

5. Comparison between measured and theoretical linewidth

In this section we compare our experimental results on the intrinsic linewidth of the lasers with theoretical predictions and try to understand how well we can predict the linewidth of these lasers.

We use the following expression derived from Patzak in [29] which describes the linewidth for semiconductor extended cavity configurations

\[
\Delta \nu = \frac{v_g^2 h v n_{sp}(1 + \alpha^2)}{4 \pi P_o} (a_m + a_i) a_m \frac{1}{C} \frac{1}{F^2},
\]

(8)

where \(v_g\) is the group velocity, \(h v\) is the photon energy, \(n_{sp}\) the spontaneous emission coefficient, \(\alpha\) is the alpha linewidth enhancement factor, \(a_m\) the distributed out-coupling loss, \(a_i\) the distributed internal loss, \(P_o\) the laser output power and the term \(F\) the linewidth reduction factor due to the extended cavity. The term \(C\) in the denominator is defined as

\[
C = \left(1 + \frac{\sqrt{R_1}}{\sqrt{R_2}} \frac{1 - R_2}{1 - R_1} \right),
\]

(9)

where \(R_1,2\) the power reflectivities of the two mirrors. It is a correction term correcting for the reflectivity imbalance between the two mirrors [12,29]. The distributed power out-coupling loss \(a_m\) is defined as

\[
a_m = \frac{1}{L_{SOA}} \ln \left( \frac{1}{\sqrt{R_1 R_2}} \right),
\]

(10)

where \(L_{SOA}\) is the length of the SOA. The distributed internal loss \(a_i\) is defined as

\[
a_i = \frac{L_{SOA} a_{SOA} + L_{passive} a_{passive} + a_{excess}}{L_{SOA}},
\]

(11)

where \(a_{SOA}\) and \(a_{passive}\) are the losses per unit length of the SOA and passive sections respectively and \(a_{excess}\) any other losses inside the cavity. In this case the excess loss includes excess insertion loss of the MMIs in the cavity and transitions between waveguides with different cross-sections.
The length $L_{\text{passive}}$ is the length of the passive section which includes passive waveguides and the effective length of the DBR mirrors calculated with $L_{\text{eff}, DBR} = \tanh(\kappa L_{DBR})/2\kappa$ [12]. The extended cavity related term $F$ is defined as

$$F = 1 + \frac{n_{g,\text{passive}}(L_{\text{passive}} + L_{\text{eff}})}{n_{g,\text{SOA}} L_{\text{SOA}}},$$

where $n_{g,\text{passive}}$ and $n_{g,\text{SOA}}$ are the group indices in the passive and active sections of the cavity respectively and $L_{\text{eff}}$ is the effective length of the ring resonator. Here it worth mentioning that in [12] the $F$ can include an additional term that we omit in this analysis. This term is

$$\frac{\alpha}{\tau_{RD}} \left( \frac{d}{d\omega} \ln(r(\omega)) \right)$$

where $\tau_{RD}$ is the round-trip time in the gain section and $r(\omega)$ the reflectivity spectrum of the mirrors. Since the reflectivity spectrum of the DBR mirrors of our device is flat in the operating wavelength range of the laser, the derivative is zero and does not contribute. For the response of the ring resonator we implicitly assume that the lasing mode is perfectly aligned in the middle of the ring resonator transmission where the first derivative is zero. Furthermore, we do not know with certainty how the lasing mode is aligned with respect to the ring transmission. We have however calculated that this term can be at most 1.5 in the case the lasing mode is aligned to the steepest section of the ring transmission which has negligible contribution to the linewidth. In Table 2 we summarize the parameters used for the theoretical calculation of the linewidth. The $\alpha$-factor of 3 is common for quantum-well active material and a spontaneous emission factor $n_{sp}$ of 2 for InP-based gain material. We furthermore assume 4 dB facet to fibre coupling loss which is used to calculate the output power of the lasers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{sp}$</td>
<td>2</td>
<td>Spontaneous emission</td>
</tr>
<tr>
<td>$n_{g,\text{SOA}}$</td>
<td>3.65</td>
<td>Group index in SOA section</td>
</tr>
<tr>
<td>$n_{g,\text{passive}}$</td>
<td>3.65</td>
<td>Group index in passive waveguide</td>
</tr>
<tr>
<td>$R_1$</td>
<td>0.92 / 0.85</td>
<td>Power reflectivity of rear mirror for 500 and 400 µm long DBR mirrors</td>
</tr>
<tr>
<td>$R_2$</td>
<td>0.85 / 0.70</td>
<td>Power reflectivity of front mirror for 400 and 300 µm long DBR mirrors</td>
</tr>
<tr>
<td>$a_{\text{SOA}}$</td>
<td>25 cm$^{-1}$</td>
<td>Internal loss in SOA</td>
</tr>
<tr>
<td>$a_{\text{passive}}$</td>
<td>3 dB/cm</td>
<td>Propagation loss in passive waveguides</td>
</tr>
<tr>
<td>$a_{\text{excess}}$</td>
<td>3 dB</td>
<td>Excess loss in the cavity</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>3</td>
<td>Alpha factor</td>
</tr>
<tr>
<td>$L_{\text{SOA}}$</td>
<td>500 / 750 µm</td>
<td>SOA length for the two SOA length variations</td>
</tr>
<tr>
<td>$L_{\text{passive}}$</td>
<td>1.640 / 1.648 mm</td>
<td>Passive waveguide length. The values are for the two DBR length variations</td>
</tr>
</tbody>
</table>

The measured Lorentzian linewidth and theoretical calculations in Fig. 6(a) are in reasonable agreement given the approximations used in the formulas such as a current density independent $\alpha$-factor and spontaneous emission factor $n_{sp}$, and values for reflectivities and losses that could not be measured precisely. The predictions for the lowest output power levels differ from the measured values by a factor below two. This discrepancy is attributed to the relative error in the measured linewidth increases for higher linewidths.

By first comparing the lowest linewidth of the two lasers with equally long SOA sections (500 µm for L2-orange and L3-yellow) we find as expected that indeed the laser with the higher reflectivity mirrors exhibits lower linewidth. Here we should note however that by changing the reflectivities of the mirrors, not only the mirror loss $a_m$ changes but also $C$ in Eq. (8) which takes into account the imbalance between the two mirrors and alters the linewidth. More specifically for reflectivity values corresponding to 400 and 500 µm long DBRs, $C$ decreases by about...
Fig. 6. (a) Measured (circular markers) and theoretically calculated (solid lines) Lorentzian linewidths of the three lasers as a function output power. (b) The calculated effective length (solid lines) for different power coupling coefficients of the ring resonator. (c) The corresponding calculated linewidth. The blue circle indicates the calculations with the current parameters of the laser, the red circle for using a 0.15 coupling coefficient with an MMI and the green square are calculations for using a directional coupler instead of an MMI. The purple square indicated the calculations for using a directional coupler and reducing the losses from 3 dB/cm to 0.4 dB/cm.

10% compared to 300 and 400 µm. Nevertheless, the linewidth is lower as expected for higher reflectivity mirrors. Furthermore, we compare the minimum linewidth of the laser with 750 µm long SOA and 300 and 400 µm long DBRs (L1-blue) with the laser with 500 µm long SOA and equally long DBRs (L3-yellow). We find that the laser with the longer SOA exhibits a lower linewidth. This seems counterintuitive since the SOA is longer and therefore internal optical loss is higher as well. However, the distributed mirror loss \(a_m\) defined in Eq. (9) is decreased thus resulting in lower linewidth. Finally, we compare the minimum linewidth of the same laser with 750 µm long SOA (L1-blue) to the laser with 500 µm long SOA and 400 and 500 µm DBRs (L2-orange). The minimum linewidth for the laser with 750 µm long SOA is lower. The same mechanism regarding the distributed mirror losses as for the previous comparison still holds. Now however, higher reflectivity mirrors are also incorporated which should decrease the linewidth. Nevertheless the minimum linewidth of the laser with 500 µm SOA is not lower as one might expect. This is ultimately a result of an interplay between the distributed mirror loss \(a_m\) defined by the reflectivities and SOA length and the factor \(C\). Finally, it should also be noted that the change of the \(\alpha\)-factor is not taken into account even though it is a current density dependent term and the minimum linewidth of the lasers are obtained at different current densities.
The linewidth floor in the measured data is not expected to be predicted by the theory since the physical process that cause it are not included. The equation predicts a continuous decrease of the linewidth with increasing power. A closer look at the blue curve and markers in Fig. 6(a) suggests that the effect causing the linewidth floor start to appear already before the minimum linewidth of 63 kHz occurs, between ~2 - 3 mW. In Fig. 6(a) the linewidth increase for the laser with 500 μm long SOA and 400 and 500 μm long DBR grating appears to be more drastic compared to the other lasers. The LI curve of this laser yields a smaller slope efficiency and lower output power due to the longer gratings. Due to the smaller slope efficiency the optical power and therefore the points in Fig. 6(a) appear to be more closely spaced to each other compared to the measured points of the other lasers. This is also evident from Fig. 5(b) where the linewidth is plotted as a function of the inverse normalised output power.

In Fig. 6(b) and 6(c) we present the estimated effective length of the ring filter \( L_{\text{eff}} \) and the corresponding theoretical calculation of the Lorentzian linewidth of the laser respectively. Given the power coupling ratio of the MMIs in the ring filter (50%) and the calculated round trip transmission coefficient (0.67), the current laser is roughly positioned where the blue circles are placed in the two plots. \( L_{\text{eff}} \) is about 0.85 mm and the predicted linewidth 53 kHz. This effective length is only 0.2 mm larger than the physical length of the ring resonator. Therefore the contribution of the ring resonator to the linewidth reduction is not very large. A linewidth improvement of a factor of almost 2 should be possible by replacing the 50-50 dB MMI with an 85-15 MMI (red circles) thereby reducing the power coupling coefficient to 0.15 from 0.5. The increase of effective length in this case is slightly over 1.8 mm.

A more significant improvement of the linewidth is possible through the increase of the ring resonator’s Q by avoiding the excess losses of the MMI couplers. These are the dominant losses in the ring resonator. In principle directional couplers can be used in the ridge waveguide technology instead of MMIs. These can be tailored for an optimal power coupling coefficient to the ring resonator and avoid the insertion losses of the MMIs. This solution is relatively straightforward, it is used routinely in other material technologies such as silicon or silicon nitride [13–15,23]. Even though in this case the power coupling is more challenging to control, it can be realized with good critical dimension control as shown in [30]. By eliminating the MMI insertion losses with the use of a directional coupler and choosing a power coupling coefficient of 0.05 an improvement of the linewidth by an order of magnitude (green squares in Fig. 6(b) and 6(c)), down to several kHz is possible. For these calculations we have not assumed any reduction of the passive waveguide propagation losses which we have kept to 3 dB/cm. Even further reduction in linewidth is possible in case waveguides with lower propagation loss are used, such as the ones demonstrated in [31]. The demonstrated propagation loss was reduced down to 0.4 dB/cm. This was achieved in a process compatible with the same InP active-passive integration technology used for the fabrication of our lasers. Assuming this propagation loss, the use of a directional coupler and a power coupling coefficient of 0.05 for the ring resonator monolithically integrated lasers with ~kHz level linewidth should be achievable.

6. Conclusions

In conclusion, we have presented experimental results of the output optical spectra and frequency noise on DBR lasers with an intra-cavity ring resonator. A very high SMSR between 60 dB to 70 dB for the whole SOA current range and minimum intrinsic linewidth of 63 kHz are reported. Our results are in good agreement with theoretical calculations for the intrinsic linewidth and our steady state spectral model. The effective length of the ring resonator is estimated to be longer by 30% than the physical path length of the ring for the given coupling coefficient of the MMIs and their insertion losses. To improve the linewidth performance of DBR lasers, a further increase of the effective length of the ring filter is required. The power coupling coefficient to the ring needs to be reduced and the round trip losses in the ring need to be decreased. Our theoretical
calculations indicate that by replacing the $2 \times 1$ 50-50 MMIs that were used, with 85-15 MMIs which are available in the standardized library of components in the integration technology we are using and thereby reducing the power coupling to 0.15, the linewidth is expected to be reduced by a factor of two. A more significant improvement of the linewidth should be possible by the use of directional couplers in order to avoid the excess insertion loss of the MMIs. We estimate that for the current propagation loss of 3 dB/cm, by using directional couplers and 0.05 power coupling to the ring resonator linewidth of several kHz level should be achievable. Further improvements in the linewidth require reduction of the propagation losses and it is estimated that ~kHz level requires reduction of propagation losses down to ~0.4 dB/cm.

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**References**