A monolithically integrated InP-based DBR laser with an intra-cavity ring resonator for linewidth reduction and SMSR enhancement

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We investigate the effect of an intra-cavity ring resonator in a DBR laser on the linewidth and output spectrum. Such a laser is fabricated using an InP-based active-passive integration technology. A linewidth of 70 kHz is measured and an SMSR above 60 dB.

Introduction

In recent years semiconductor continuous wave narrow linewidth lasers have become increasingly important in a number of applications. Amongst others, these include telecom applications that need to operate using high order modulation formats, RF signal generation, metrology and sensing applications where reduced linewidth enables higher resolution. Different integration technologies, material systems and design strategies have been used to improve the linewidth. Sub-kHz intrinsic linewidths, below 300 Hz have been demonstrated by an extended cavity laser using the hybrid combination of silicon nitride and III-V materials [1]. An extended cavity laser with 2.5 kHz intrinsic linewidth was reported using hybrid-bonded integration of III-V on silicon [2].

In this paper we investigate the effect on the linewidth and spectral output of a ring resonator placed inside the cavity of a multi-section DBR laser. The laser is designed in a commercially available InP-based active-passive generic integration technology [3]. First, the cavity design strategy and modelling are given and then the experimental measurements of VLI curves, side-mode suppression ratio and linewidth are presented. Finally, we compare the data with theoretical predictions and discuss possible improvements.

Laser cavity design and modelling

According to Schawlow-Townes-Henry formula [4], in order to reduce the linewidth of any laser the photon lifetime inside the cavity must be increased. There are two ways towards achieving this. The first is to minimize absorption and scattering losses inside the

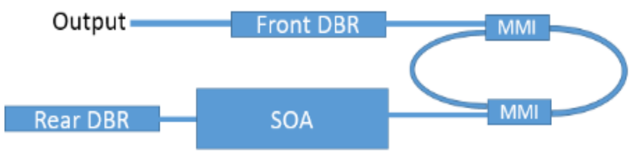

Figure 1. Schematic of the laser.

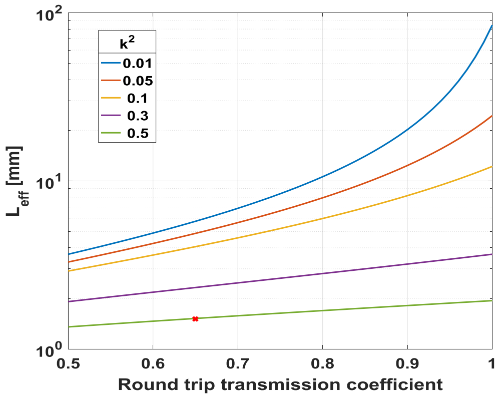

Figure 2. Calculated effective length as a function of round trip transmission coefficient for different power coupling coefficients.

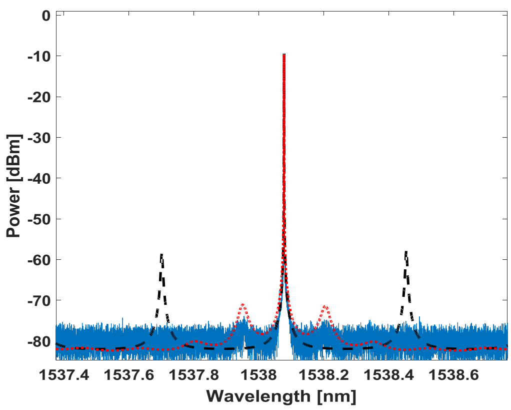

Figure 3. Recorded laser spectrum (blue), calculated spectrum for the DBR laser with an intra-cavity ring resonator (red) and calculated spectrum for DBR laser (black).

laser cavity and the second to increase the cavity length. The ultimate limit of physical length increase is eventually dictated by the absorption and scattering losses.

Here, we focus on increasing the effective length of the cavity [5] instead of the physical length, by adding an intra-cavity ring resonator within a DBR laser. A schematic of the laser cavity that has been realised is shown in Fig.1. The cavity is formed by the two distributed Bragg reflectors (DBR) and it includes a semiconductor optical amplifier (SOA), a ring resonator and passive waveguides. The DBR gratings have a 50% fill factor, a designed coupling coefficient of 50 cm^{-1} and they are 300 and 400 μm long. Their reflectivities are estimated to be 75% and 95% respectively. The SOA length is 500 μm long. The ring resonator is formed by 2x1 multimode interference couplers (MMI) which are also used to couple light in and out of the resonator. The power splitting ratio of the MMIs is 50%. We can expect the ring to be over-coupled due to this high value. . In the designing procedure we tried to minimize both the circumference of the ring resonator and the cavity length in order to keep the ring free spectral range (FSR) of the ring and cavity mode spacing as large as possible. In this way we found the lasing mode can experience a higher round trip gain compared to its neighbours as compared to modes with smaller spacing. The 2x1 MMIs were chosen instead of 2x2 MMIs because they are shorter and the arcs' radius is 80 μm which is about the minimum with low bending losses (~0.1dB per 90˚). The result is a ring with 128 GHz FSR and a laser cavity mode spacing of approximately 0.1 nm.

A steady state spectral model [6] was developed in order to estimate the output spectrum of the laser. Using this model we calculate the output spectrum of the laser at threshold. The model is based on a transfer matrix (T-matrix) formulation. Every element in the cavity (SOA, ring resonator, passive waveguide) is described by a wavelength dependent T-matrix. By imposing the boundary conditions (DBR mirrors which are also described by T-matrices) and adding the amplified spontaneous emission, the steady state amplitude of the envelope of a monochromatic single transverse mode is calculated. The field amplitude is calculated for a range of wavelengths for a specific SOA gain. The SOA gain is gradually increased until the round trip gain reaches unity somewhere in the wavelength range. At this point the laser reaches threshold. In Fig. 3 the calculated spectrum for a DBR laser with an intra-cavity ring resonator and a multi-section DBR laser is shown. Despite the longer cavity length, the DBR laser with the intra-cavity ring resonator is expected to show a higher side-mode suppression ratio (SMSR). This is due to the wavelength selectivity that the ring offers. Even though the neighbouring cavity modes are closer to the lasing mode (by almost a factor of 3) they are further supressed compared to the shorter laser with DBRs only.

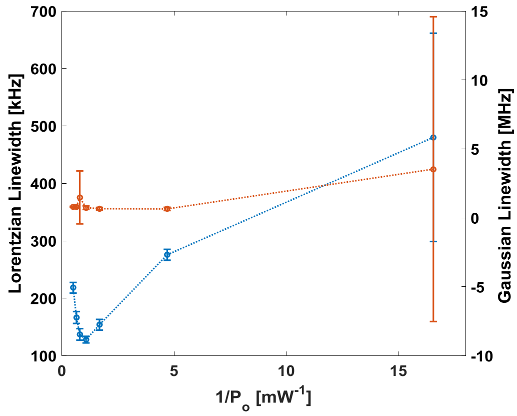

Figure 4. Lorentzian (blue) and Gaussian (orange) linewidths as a function of inverse output power. Measured using delayed-self heterodyne method.

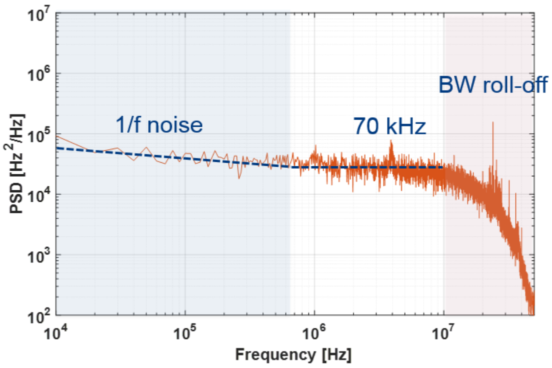

Figure 5. Frequency noise power spectral density. The flat region multiplied by π is the intrinsic linewidth of the laser. It is calculated to be 70 kHz.

Laser characteristics and discussion

The laser and an independent but identical ring resonator were fabricated in a multi-project wafer run by Smart Photonics [4] and were characterized at 18 ˚C. The transmission of the ring resonator was characterised. It showed a quality factor (Q = ω/Δω) of about 5500 and a finesse of 5. The round trip transmission coefficient was extracted and found to be about 0.67 at the resonance wavelength (-1.7 dB). Most of the loss is attributed to the insertion loss of the MMIs where the excess loss is typically measured to be between 0.5 and 1 dB. Moreover, from the contrast between the peaks and dips of the ring resonator spectrum which is about 8 dB, we can confirm that the ring is heavily over-coupled which leads to a decrease in effective length (Fig. 2). From the extracted parameters the effective length of the ring resonator was calculated to be about ~2.5 mm thus an enhancement factor of almost 3 compared to the physical length (Fig. 2, red cross).

The threshold current is 15 mA. The maximum output power of the laser exceeds 5 mW at 100 mA, estimating the coupling losses from the chip facet to the lensed fibre to be at least 4 dB. A spectrum at 22 mA is shown in Fig. 3 (blue trace), recorded with a high resolution optical spectrum analyser with a resolution of 5 MHz. The spectrum is in reasonable agreement with our model and exhibits an SMSR of 65 dB (Fig. 3, red dashed line). The neighbouring cavity modes are just visible above the noise floor of the spectrum analyser. The SMSR is maintained above 60 dB for the whole current range up to 100 mA.

Linewidth measurements were carried out using the delayed-self heterodyne (DSH) method with a delay line of 25 km. The measurements were taken at different SOA current levels thus different optical output powers and a Voigt function was fitted to the electrical spectra. The goal of measuring the linewidth under different conditions is twofold; first find the minimum linewidth of the laser and second to easier distinguish between the Lorentzian (intrinsic) linewidth and the Gaussian one (the technical noise should remain roughly constant). In Fig. 4 the two linewidths are presented as a function of the inverse output power. The markers indicate the average of ten samples and the error-bars represent their standard deviation. With increasing output power (increasing SOA current) the Lorentzian linewidth (blue markers) is decreasing. The minimum is 130 kHz at a 40 mA current. Above this current a linewidth floor is encountered. The linewidth floor in semiconductor lasers is a known phenomenon which however lacks explanation.

To study in more detail the intrinsic linewidth of the laser we measure the frequency noise power spectral density. The white noise part of the single side spectrum multiplied by π corresponds to the Lorentzian linewidth. Our measurements show that the intrinsic linewidth is about 70 kHz compared to 130 kHz as measured with DSH. We attribute this difference to the 1/f noise in combination with our fitting. From the frequency noise spectrum, the 1/f noise is visible in Fourier frequencies above 10 kHz while our DSH delay measures 1/f noise from 8 kHz.

Further improvement

Using the modified Schawlow-Townes formula [4], an alpha factor of 2.2 is estimated for the 70 kHz linewidth. This value matches very well to the intrinsic linewidth extracted from the frequency noise measurements. To further decrease the linewidth the effective length of the ring resonator should be increased. From Fig. 2 it is evident that such improvement can be achieved by minimizing the round trip losses and/or decreasing the power coupling coefficient. Both can be achieved by replacing the MMIs with directional couplers. In this way we can reduce the round trip losses by at least 20% and at the same time the coupling factor can be optimised. E.g. with a coupling of 5% an effective length improvement of a factor of 20 can be achieved leading to a further linewidth reduction by an order of magnitude. The downside of this solution at the moment is poor reproducibility of the performance of the directional couplers due to fabrication issues.

Conclusion

We have presented a DBR laser with linewidth down to 70 kHz and SMSR exceeding 60 dB. The effective length of the ring resonator is limited to about 3 times its physical length. To further increase it, the round trip losses in the ring need to be decreased and the coupling coefficient needs to be modified. By replacing the MMIs with directional couplers, an improvement of an order of magnitude in the linewidth should be possible.

References

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