Investigation into linewidth reduction of InP DBR lasers with an intra cavity ring resonator

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Abstract

We present the theoretical analysis for the design of integrated narrow linewidth semiconductor lasers which include an intra cavity ring resonator and are to be fabricated on the Smart Photonics InP platform. The intrinsic linewidth of a laser is inversely proportional to the length of the lasing cavity. Intra cavity ring resonators are a popular method to increase the effective length of a laser cavity and thus reducing the intrinsic linewidth whilst still maintaining the physical length and single mode operation. On the InP platform, where directional couplers are not yet available, Multi-Mode Interference (MMIs) couplers are instead used to couple light in and out of the ring. We demonstrate how the properties of the MMIs, their power coupling coefficients, lengths, and losses, impact on both the lasers linewidth and emitted power. Our simulated results predict that by using 85%:15% MMI 2x2 couplers in the ring resonator, instead of the more common 50%:50% 1x2 MMI couplers, we can increase the effective length of the ring from 0.72mm to 2.6mm. In doing so, we predict a reduction of the intrinsic linewidth of our laser by more than a factor of 3 to less than 10kHz at 5mW output power.

Introduction

Narrow linewidth, continuously tunable semiconductor lasers are crucial components in precision sensing, where a physical property of a system, for example distance or strain, is determined through a measurement of the light returning from an interferometer type sensor, e.g., it's frequency or amplitude. To achieve high resolution sensing, narrow linewidth (<100kHz) lasers are prerequisite.

The frequency noise power spectral density of a semiconductor laser can be separated into two regimes which contribute to linewidth broadening [1]. At low frequencies technical noise is dominant, resulting from processes, other than the lasing operations, that take the form $1/freq^{\alpha}, \alpha > 1$. Technical noise can be reduced through frequency stabilization techniques [2]. At higher frequencies, laser linewidth is limited by intrinsic noise. Frequency independent intrinsic noise results from fluctuations to optical phase for which there are two contributing factors: 1) spontaneous emission events which result in incoherent photons and a change in the intensity of the field and 2) changes in optical field intensity. The effect of these factors is given in equation (1) which yields the intrinsic linewidth for extended cavity lasers [3].

$$\Delta f = \frac{{v_g}^2 \hbar \upsilon n_{sp}(1+\alpha^2) \cdot a_m(a_m + a_i) \cdot F \cdot C}{4\pi P_O} \qquad (1)$$

Accounts for frequency dependent reflectivity, $F = \left[1 + \left(\frac{n_P(L_{passive} + L_{dbr,eff})}{L_G \cdot n_G}\right)\right]^{-2}$ (2)

Internal loss, $a_i = \frac{L_G a_G + L_{passive} a_{passive} + a_{excess}}{L_G}$ (3)

Average mirror loss, $a_m = \frac{1}{L_G} \ln\left(\frac{1}{\sqrt{R_2}\sqrt{R_1}}\right)$ (4)

Where α is the linewidth enhancement factor, n_{sp} is the spontaneous emission factor, P_O is the power out coupled from the laser, v_g is the group velocity, C accounts for asymmetry in the reflectivity of the two mirrors, R is the reflectivity of the DBR mirrors, $L_{passive}$ is length of passive waveguide and effective length of the ring resonator and L_G is the length of gain section.

Through equations 1, 2 and 3 one can see that linewidth is proportional to the optical losses per unit length. Increasing the length of the passive waveguides comes at the expense of decreasing the interval between cavity modes, the FSR, which will result in an increase in the side mode suppression ratio and amplitude noise, thus jeopardizing the realization of single mode operation. However, the effective length of the cavity can be extended, and the other cavity modes suppressed through the introduction of a ring resonator a grating or a combination of the two [4]. In this paper we present the design of dual DBR laser with an intra cavity ring resonator to extend the effective cavity length and reduce the linewidth.

Cavity design

Figure 1 depicts our design of laser. On the InP platform, where effective directional couplers are not available, we have used MMIs to couple light into and out of a ring. Figure (2) shows a diagram of our ring resonator. The electric field, E1 enters through port 1. The strength of coupling in the MMI couplers cross state (blue) is described by the power coupling coefficient, 'κ', whilst the strength of light in the bar state (red) is described by the self-coupling coefficient 't'.

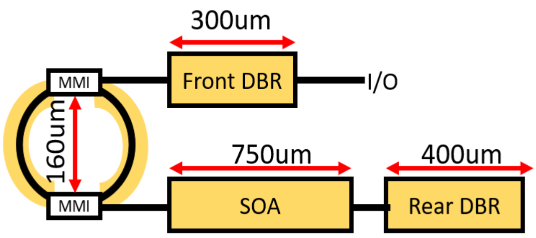


Figure 1: Dual DBR laser with intra ring resonator. Gold representing tuneable

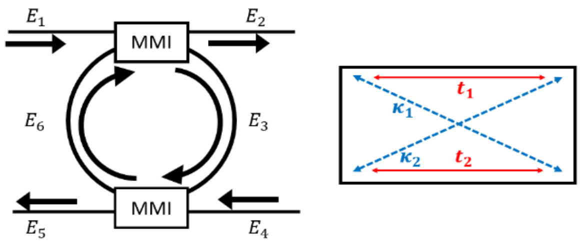


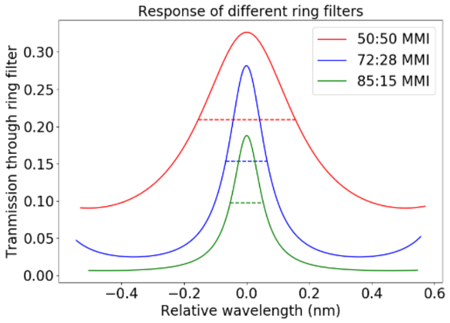
Figure 2: a) MMI coupler ring resonator, b) MMI coupler indicating cross and bar states.

The electric field transmitted through the ring is given below [5].

$$E_5(\lambda) = E_t = \frac{-\sqrt{\kappa}\sqrt{\kappa^*}\sqrt{\alpha_r}\, e^{\frac{j\theta}{2}}}{1 - \sqrt{t^*}\sqrt{t^*}\alpha_r e^{j\theta}}\, E_1 \quad (5)$$

Where $\theta = \frac{2\pi n_g L}{\lambda}$, $\alpha_r = 10^{-0.1 \cdot I_{loss}} \cdot t^* \cdot e^{L \cdot a \cdot \ln(10) \cdot 0.1}$, where a is the attenuation, α_r is the round trip electric field loss, I_{loss} is the insertion loss, L is the circumference of the ring and we assume $E_4 = 0$.

Equation (5) demonstrates the relation between the magnitude of the field transmitted and the value of κ. Decreasing the power coupling coefficient (κ) acts to increase the amount of light circulating in the ring, consequently decreasing the intensity of the E field transmitted and providing high Q factor resonator. Correspondingly, the greater the number of round trips the light undergoes in the ring, the greater the total phase delay causing an increase in the effective length of the ring.



MMI coupler	Peak power	FWHM (nm)	FSR (nm)	Finesse
1x2 50:50	0.327	0.311	0.977	3.14
2x2 72:28	0.188	0.133	0.880	6.62
2x2 85:15	0.153	0.105	0.810	7.71

Figure 3: Transmission through the three different ring resonators. Table 1: characterizes the response of the different ring resonators.

Figure 3 and Table 1 demonstrate how the transmission through the ring filter decreases with the power coupling coefficient of the MMI. We see a reduction of more than a factor 2 when the 85:15 MMI coupler is used in place of the 50:50. Therefore, we can expect a lower output power of lasers using MMIs with lower power coupling coefficients.

Linewidth Simulation

Table 2 details the MMIs (with deeply etched side walls) that are used in each of our three dual DBR ring resonator laser designs. We simulate the expected effective length of each the rings and use this to extract the linewidth for each laser cavity design.

MMI	Length (um)	Circumference of ring (mm)	FSR (kHz)	t	κ	α_r
1x2 50:50	72.00	0.647	122	0.50	0.50	0.628
2x2 72:28	107.65	0.718	110	0.72	0.28	0.753
2x2 85:15	139.48	0.782	101	0.85	0.15	0.818

Table 2: Properties of MMI couplers used in the ring resonator design.

Figure 4 shows the magnitude and phase of the electric field transmitted through the ring resonator for a symmetric MMI coupler ($\kappa = t = 0.5$).

The phase of electric field transmitted through the ring is given by

$$\varphi = \arg(E_t) \qquad (6)$$

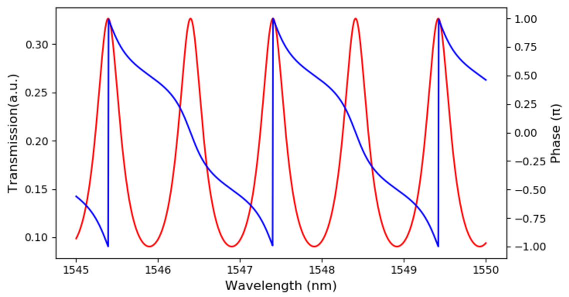


Figure 4: Transmission and phase of the electric field transmitted through ring resonator using 50:50 MMI coupler.

The effective length can then be determined by taking the derivative of phase with respect to the wavelength $\frac{d\varphi_d(\lambda)}{d\lambda}$. The steeper this gradient, the greater the phase delay experience and hence the effective length of the ring resonator.

$$L_{eff}(\lambda) = \frac{d\varphi_d(\lambda)}{d\lambda} \cdot \frac{\lambda}{\beta} \qquad (7)$$

Figure 5a) show the effective length of the ring resonator against the relative wavelength for each of the MMIs. The values for the effective length on resonance is given in Table 3. The dots in the figure 5a), indicate the physical length of each ring resonator.

By extracting the value for the effective length of the ring resonator on resonance, we can determine the lasing linewidth. For this we follow the formalisation first established by E. Patzak et al [3] and later used by T.Koch [6], given in equation (1).

MMI	Physical length (mm)	Effective length at resonance (mm)	Linewidth at 5mW (kHz)
50:50	0.643	0.747	37.0
72:28	0.645	1.450	11.0
85:15	0.718	2.600	6.20

Table 3: The physical length, effective length on resonance, and predicted intrinsic linewidth at 5mW.

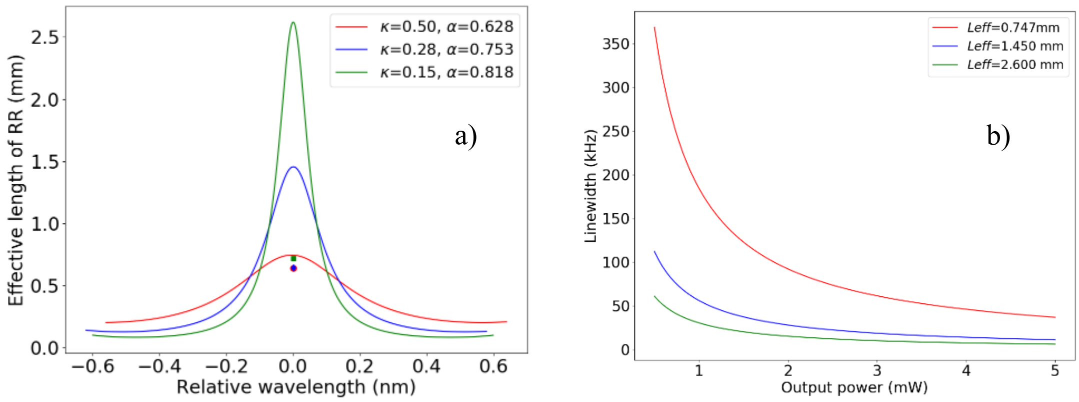


Figure 5: a) Effective length of Ring resonator against the normalised wavelength, b) Intrinsic linewidth against output power for the DBR RR laser with different effective lengths.

For each laser cavity design the theoretical linewidth against output power is shown in figure 5b). The value at 5mW of output power is given in Table 3. The linewidth of the 85:15 coupler (in green) is lower than that of the other two couplers for all output powers. Furthermore, at 5mW see an expected reduction of linewidth of factor 6 when compared to the 50:50 MMI coupler to a value of 9.6kHz.

Conclusion

Our calculations have shown that a dual DBR laser with an intra cavity ring resonator that uses MMI couplers with lower power coupling coefficient, κ, reduces both the intrinsic linewidth and transmission through the ring. For $\kappa = 0.15$, we predict sub 10kHz intrinsic linewidth for output powers greater than 3mW. The designs discussed in this paper have been fabricated and the simulated results will be experimental verified shortly.

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