Feedback insensitive integrated semiconductor ring laser concept using weak intracavity isolation

T.T.M. van Schaijk, D. Lenstra, E.A.J.M. Bente and K.A. Williams

***Abstract*—External optical feedback can influence semiconductor laser performance to a great extent. Strong optical isolators with reasonable insertion loss are not available in a photonic integrated circuit due to material incompatibilities, preventing the use of an isolator external to the laser cavity to suppress any feedback effects. In this work the feedback sensitivity of a semiconductor ring laser with an intra-cavity isolation of less than $10\,\mathrm{dB}$ is studied using a rate equation analysis. It is found that the relative intensity noise and linewidth are insensitive to feedback strengths over $-10\,\mathrm{dB}$.**

For many applications it is desirable to make an integrated laser insensitive to the effects of external optical feedback (EOF). Usually this is achieved by placing one or two Faraday isolators in series with the laser, such that EOF can be suppressed by up to $60\,\mathrm{dB}$ as is required to sufficiently reduce the effects of the EOF [1]. Such isolators currently cannot be integrated on a photonic integrated circuit (PIC) without insertion losses of tens of dBs and are therefore not suitable for providing feedback insensitivity.

This work presents the analysis of a novel integrated ring laser that is inherently insensitive to feedback by employing an intra-cavity, optical isolator with several dB of isolation only. It is demonstrated in [2] that on-chip isolation on the order of $10\,\mathrm{dB}$ can be achieved. The isolator introduces a loss difference between the clockwise (cw) and counterclockwise (ccw) modes, increasing the lasing threshold for one mode with respect to the other mode and forcing the laser to operate unidirectionally in the mode with the lowest losses. Without loss of generality, it is assumed this mode is the cw mode. As illustrated in Fig. 1, any EOF will return to the suppressed ccw mode. Furthermore, assuming no direct interaction between the cw and ccw mode inside the laser cavity, the only effect that EOF has on the lasing mode is through changes in the number of charge carriers in the semiconductor optical amplifier (SOA).

The rate equation analysis reported here follows the procedure outlined in [3] closely. First a set of five differential equations describe the changes in optical intensities and phases for both modes as well as the number of charge carriers in the SOA. It is assumed that the spectral filter is sufficiently narrow, such that only one longitudinal mode needs to be considered for each propagation direction. The slowly varying envelope approximation is used and the effects of feedback are accounted for similarly to as was done in [4] for a linear laser. The resulting model allows to obtain the intensity and instantaneous frequency of both the cw and ccw modes. The on-chip isolation is modeled by a gain difference between the cw and ccw modes induced by the isolation.

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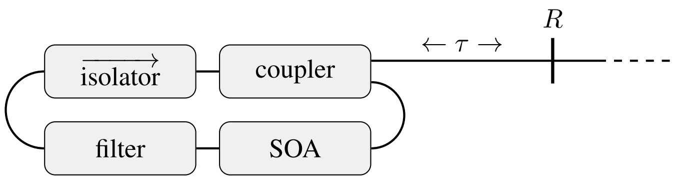

Figure 1. Schematic representation of laser cavity consisting of weak optical isolator, an outcoupler, a semiconductor optical amplifier and a spectral filter. The feedback delay time τ and the reflectivity of the external reflector R are indicated.

Steady state

The steady state conditions are derived by equating the time derivatives of the rate equations to zero. The resulting set of equations is numerically solved from which the steady state quantities are obtained as a function of the feedback rate. To this end reasonable values for the parameters were used. The injection current was taken to be $16\,\mathrm{mA}$ above the threshold, while the photon lifetime was assumed to be $10^{-11}\,\mathrm{s}$. The feedback delay time τ was assumed to be $100\,\mathrm{ns}$. A cavity length of $2\,\mathrm{cm}$ was assumed to include the rather long length of the intra-cavity isolator [2].

The resulting values for the steady state intensities are shown in Fig. 2. It is seen that the power in the cw mode decreases for increased EOF while the power in the ccw mode increases. This is caused by the increase in effective gain of the ccw mode for increasing EOF. Because both modes share a common reservoir of charge carriers, the stronger ccw mode causes a

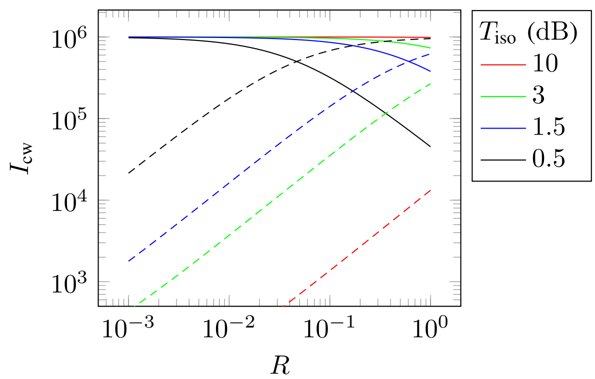

Figure 2. Intensities for the cw (solid) and ccw (dashed) modes for four values of intra-cavity isolation.

reduction of the gain for the cw mode of which the intensity is reduced.

It is also seen that an increase in isolation reduces these effects. This is expected because the increased isolation suppresses the ccw mode more strongly. For 3 dB of isolation the effects of EOF become negligible for feedback strengths below −10 dB, while for 10 dB of isolation the steady state intensity of the laser is only negligibly influenced even if all the light returns to the cavity, making the laser essentially insensitive to feedback.

DYNAMICS

To study the relative intensity noise (RIN) and linewidth of the laser, the effects of spontaneous emission are added via Langevin terms in a similar fashion as in [5] and [6]. This results in a perturbation to the steady state. The fluctuations in the intensity of the cw mode result in the RIN, while fluctuations in the phase, and therefore frequency, result in the linewidth of the laser. Both these quantities are again dependent on the amount of isolation and the feedback strength.

The calculated RIN-spectrum is plotted in Fig. 3 as a function of frequency at 3 dB isolation and for various feedback strengths. This figure shows that the most important change in RIN occurs at low frequencies. The relaxation oscillation frequency is clearly visible as the peak. Especially for high amounts of feedback, there is a clear ripple in the spectrum. This ripple is caused by a resonance via the cw mode, external reflection, ccw mode and the charge carriers. The frequencies at which these resonances occur are directly related to the feedback delay time τ. Increasing amounts of EOF mainly result in an increase in the RIN at low frequencies. This is illustrated in Fig. 4, where the low-frequency RIN is plotted against the feedback strength for various amounts of isolation.

The linewidth is obtained as the low frequency limit of the power spectral density of the phase noise and is plotted against the feedback strength for various amounts of isolation in Fig. 5. It is clear that the linewidth increases for increasing EOF. This figure also shows that this effect is mitigated by an increase in intra-cavity isolation. Most of the linewidth increase can be attributed to the decrease of the intensity of the cw mode.

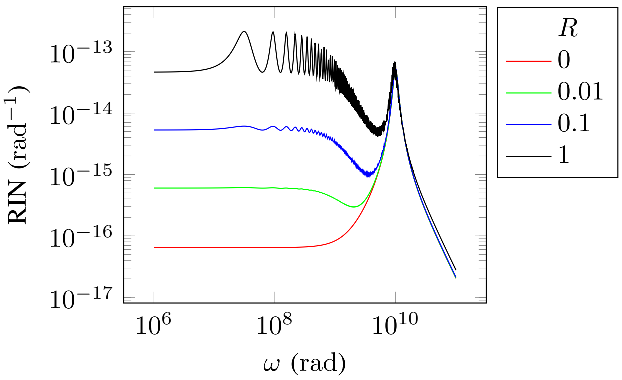

Figure 3. RIN-spectrum for 3 dB isolation and for four feedback reflectivities as indicated in the legend.

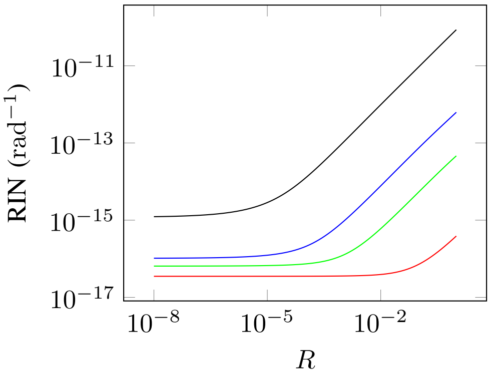

Figure 4. Low frequency RIN as a function of the feedback reflectivity R for four values of isolation (color codes indicated in the legend of Fig. 2).

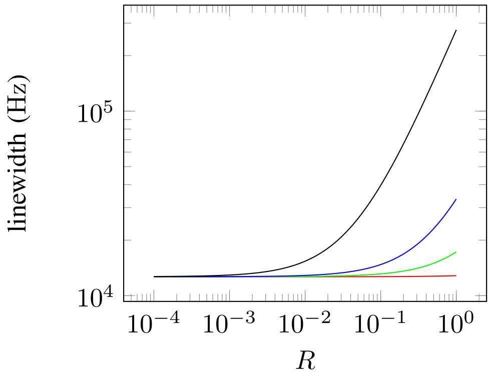

Figure 5. Linewidth of the cw mode as a function of the feedback reflectivity R for four values of isolation (color codes indicated in the legend of Fig. 2).

CONCLUSION

Weak isolation of 3 to 10 dB can be achieved on-chip [2], and is sufficient to realise a feedback insensitive integrated laser. This opens the road to integrating the laser in more complex structures, where the detrimental influence of on-chip reflections would prohibit its application otherwise. The RIN of the presented laser was calculated to be 6.4×10^{-17} rad^{-1} and the linewidth 1.3×10^{4} Hz. Even for more than −10 dB feedback reflectivity and 10 dB of isolation these values were calculated to be stable, eliminating the need for a much stronger external optical isolator.

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