Inversion dependent non-linear coupling in laterally coupled semiconductor lasers

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Our simulations show that the bifurcation points of a twin-stripe laser are influenced by the inversion dependence of the coupling rate between the fields in the two ridges.

Introduction

The study of coupled semiconductor lasers is gaining in popularity, both due to the drive towards integrated optical components, but also due to the large variety of dynamics that coupled lasers can exhibit [1]. Since the integration of optoelectronic devices requires the placement of multiple components on a single chip, these components are generally, intentionally or unintentionally, coupled to some degree and therefore the underlying physics of coupled semiconductor lasers is of great interest also for integration technology.

Here, we will present the simulation of two laterally coupled Fabry-Perot type semiconductor lasers, separated by about 4 μm, the so-called twin-stripe lasers. For an in-depth analysis of these devices we refer to [2]. We will investigate the effects on the dynamics of an inversion dependant coupling between the lasers. It has earlier been shown that two main mechanisms for coupling exist for coupling of the field in twin-stripe lasers: coherent coupling of the optical fields and incoherent coupling, where the gain of one laser contributes with stimulated emission photons to the field of the neighboring lasers [3]. Our emphasis will be on the coherent type of coupling. In a rate-equations type of description the coupling strength between the two laser stripes is quantified by the coupling rate. So far, it was assumed that this coupling is constant and independent of the carrier fluctuations in each stripe. However, recent theoretical work, using coupled wave-guide theory has shown that the inversion dynamics will cause the coupling rate to fluctuate and alter the coupling strength.

In the next section we present a short overview of the underlying theory and the simulation conditions, followed by presentation of the results. We will end with some concluding remarks.

The coupling rate

The rate equations for a twin-stripe laser were presented in [4]. They describe the temporal evolution of the slowly varying field envelopes of the different modes in the lasers and the evolution of the inversion moments attributed to the longitudinal modes. To simplify the analysis and the derivation of the inversion dependent coupling, we will here restrict ourselves to the single longitudinal mode and identical stripe limit. Each laser stripe is assumed to sustain a single longitudinal mode, the slowly varying field envelope of which evolves as:

$$\dot{E}_1(t) = \frac{1}{2}(1+i\alpha_{11})\xi_{11}\rho_1(t)E_1(t) + \frac{1}{2}(1+i\alpha_{12})\xi_{12}\rho_2(t)E_1(t) + \frac{1}{2}(g_1 - \Gamma_1)E_1(t) + \kappa E_2(t)e^{i\varpi t}$$

$$\dot{E}_2(t) = \frac{1}{2}(1+i\alpha_{22})\xi_{22}\rho_2(t)E_2(t) + \frac{1}{2}(1+i\alpha_{21})\xi_{21}\rho_1(t)E_2(t) + \frac{1}{2}(g_2 - \Gamma_2)E_2(t) - \kappa E_1(t)e^{-i\varpi t}$$

Here $E_x(t)$ denotes the slowly varying field envelope of the relevant longitudinal mode in stripe x and $\rho_x(t)$ its inversion moment, the equation for which is not presented since it is not relevant for the current analysis. For a deeper discussion of these rate equations, we refer to [4]. The rest of the parameters and their description are denoted in Table I. The coherent coupling between the fields in the two laser stripes is described by κ, which in [5] is related to the physical parameters of the laser, such as the size of the optical cavity and the refractive indices of the different sections in the device. Furthermore, in [6] it is shown that in presence of gain, the coupling rate is dependent on the inversion moments of the two stripes as:

$$\kappa = \kappa_0 (1 + \varepsilon_1 \Delta\rho_1 + \varepsilon_2 \Delta\rho_2),$$

where κ_0 is the coupling rate in absence of inversion fluctuations, which can be taken to be the coupling rate at threshold, and $\Delta\rho_1$ and $\Delta\rho_2$ are the inversion fluctuations relative to their values at threshold. The relative importance of these fluctuations in the coupling rate are described by the parameter $\varepsilon_{1,2}$ (see [6] for the derivation of $\varepsilon_{1,2}$). For a 4 μm distance between the two stripes, $\varepsilon_{1,2}$ is ~ 0.01, but it is strongly dependant on the transverse field overlap between the fields in the two stripes and may grow substantially if the distance between the stripes is decreased or the field confinement in the stripe deteriorates. We will here present simulations for $\varepsilon_{1,2}$=0, 0.01 and 1.0 to investigate several different scenarios.

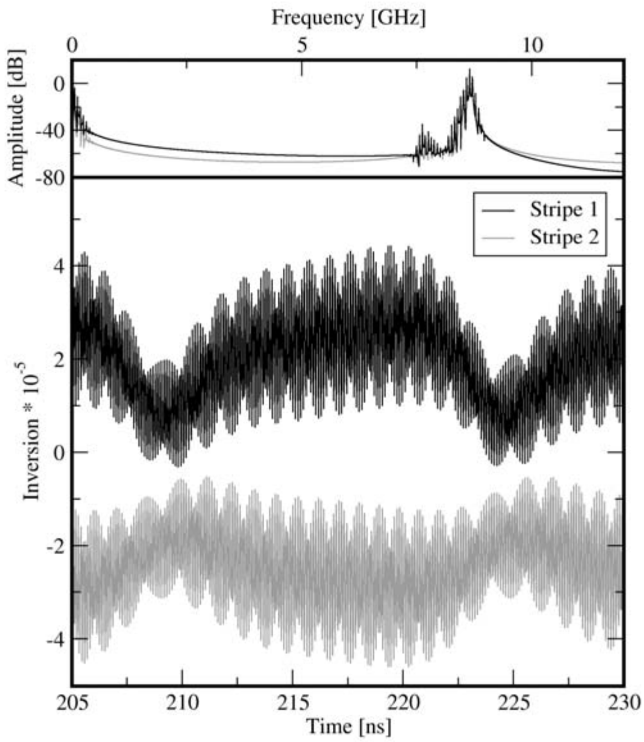

Figure 1: A sample of the dynamics at the bifurcation point under study. The top panel shows the RIN spectrum of both stripes and the lower panel shows a 25 ns long timeseries of the inversion dynamics of both stripes. Note the anti-phase dynamics between the stripes.

Earlier work has revealed that the two stripes in a twin-stripe laser will generally show self-oscillation type of dynamics due to mutual injection, with the frequency of oscillations being the related to the detuning between the modes in the two stripes [5]. As the detuning is decreased, the system enters a resonant regime and the dynamics gradually become more complex [7], of which one sample is shown in Figure 1. The parameter values for the simulations are listed in Table I and no noise was included in the simulations.

The top panel in Fig 1 shows the Relative Intensity Noise (RIN) spectrum, where several frequencies can be identified. The most prominent of these peaks is the one at ~8 GHz, corresponding to the optical coupling induced dynamics. The surrounding smaller peaks in the spectrum reveals that the system is exhibiting a quasi-periodic type of dynamics, which can be verified by inspection of the timeseries in the lower panel. We have traced this specific dynamical behavior to the origin of its bifurcation in parameter space, and investigated the effects of inversion dependent coupling rate on this bifurcation point.

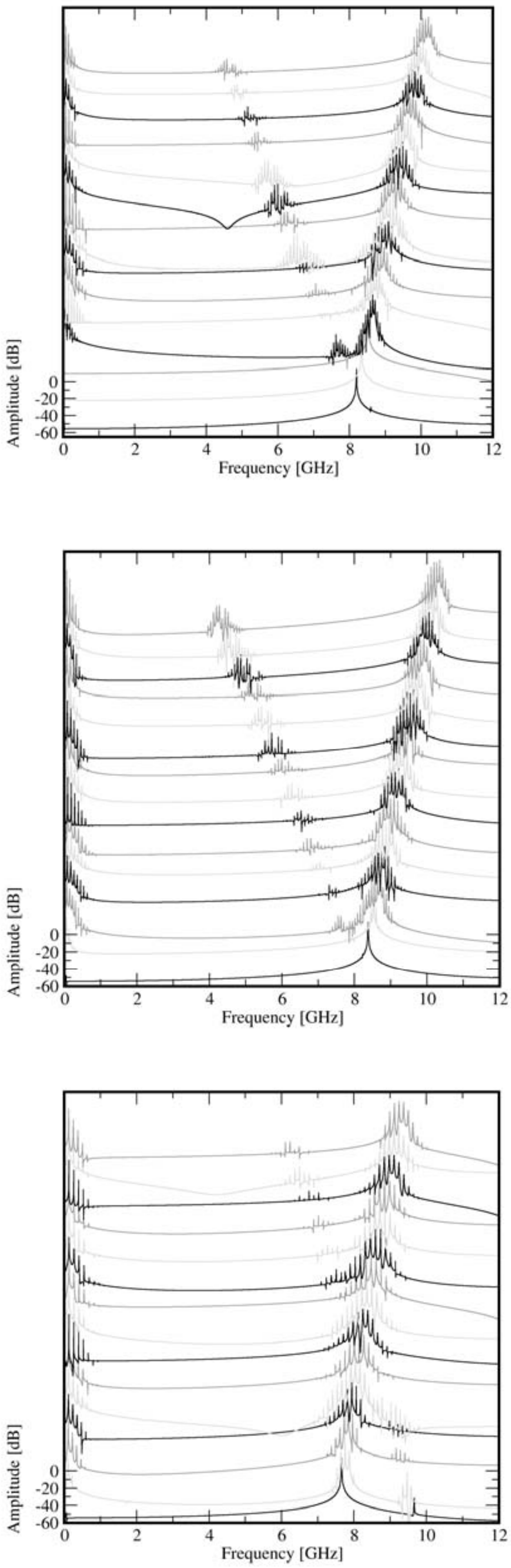

Figure 2: RIN spectra of stripe 1 at the bifurcation point, with (a) $\varepsilon_{1,2}$=0, (b) $\varepsilon_{1,2}$= 0.01 and (c) $\varepsilon_{1,2}$=1.0 .

Figure 2(a) shows the bifurcation sequence by means of the RIN spectrum. Here, the pump current of stripe 1 fixed at 40 % above threshold and the pump current of stripe 2 was increased from 40 % above threshold, in steps of 0.5 mA (bottom to top in Fig 1(a)). It should be emphasized that the smaller 'bunch of peaks' in the traces corresponds to the injected field from the side stripe and is therefore a good indication of the detuning between the two stripes. At a certain moment the two stripes are resonant (lowest trace Fig 2(a)) and do not react to each other except for self-oscillation type of dynamics. As the detuning is increased (bottom to top in Fig 2(a)), the mutual injection introduces more complex dynamics, as can be deduced from the spectra. The exact nature of these dynamics is beyond the scope of this paper, instead we will here concentrate on the movement of the bifurcation point in parameter space due to non-zero $\varepsilon_{1,2}$. Fig 2(a) is therefore a reference plot and indicates the position of the bifurcation point for $\varepsilon_{1,2}$=0, which is about 1 mA after zero detuning (third trace from the bottom).

In Fig 2(b) $\varepsilon_{1,2}$=0.01 and the bifurcation point has moved 0.5 mA closer to zero detuning. Note that the subsequent spectra are very similar to those of Fig 2(a), except for the 0.5 mA lag. To emphasize the effect of the inversion dependent coupling rate, we increased $\varepsilon_{1,2}$ to the unrealistic value of 1.0. This case corresponds to a large field overlap in the lateral direction between the fields of the two stripes and would thus require a very small distance between the stripes (~0.5 μm and very low field confinement factor). The bifurcation now precedes the zero detuning case (sixth trace from bottom in Fig 2(c)) by ~ 3 mA and dynamics are now induced even before the bifurcation point of Fig 2(a).

We have also studied cases with $\varepsilon_{1,2}$ between 0.01 and 1.0 (not shown) and have generally observed that a non-zero $\varepsilon_{1,2}$ will move bifurcation points in the parameter space as compared to $\varepsilon_{1,2}$=0 case. The magnitude of $\varepsilon_{1,2}$ decides how far the bifurcation point will be moved.

Normally, the two ridges in a twin stripe lasers are between 2 and 10 μm apart and correspond to $\varepsilon_{1,2} \leq 0.01$. Therefore, the inversion dependence of the coupling rate can be neglected in these devices. However, ridge waveguides which are 1 μm apart or less are not unusual on photonic integrated circuits and for these cases $\varepsilon_{1,2} > 0.01$, which may cause fluctuation of the coupling rate with inversion fluctuation and thus change the nature of the dynamics.

Conclusions

On of the ‘hot topics’ in photonics currently is the study of coupled semiconductor lasers, where laterally coupled semiconductor lasers form a subset. It has been shown that the two lasers in a twin-stripe laser couple, due to overlap of their optical fields in the passive section between the two stripes. In the lowest order approximation, the corresponding coupling rate is constant. However, recent work has revealed that there also exists a non-linear coupling between the two lasers, which is dependant on the inversion levels in each laser stripe.

We have presented simulations that confirm this result and have identified its influence on the bifurcation points of the system. Our simulations show that the inclusion of the inversion dependence of the coupling rate in the modeling will alter the bifurcation scenario in parameter space and move bifurcation points. This effect will grow with the magnitude of the coupling parameter $\varepsilon_{1,2}$. However, the inversion dependence of the coupling rate may be neglected in the current generation of twin stripe lasers with weak coupling and will only play a substantial role if the coupling strength between the stripes increases. This is dependant among other factors on the distance between the two stripes, the field confinement factor and the index step of the passive material separating the two stripes.

Table 1: Parameters that were used in the simulations, a,b $\in$ {1,2}.

Parameter	Stripe I	Stripe II	Description
α_{aa}	3.0	3.0	Self-linewidth enhancement factor
α_{ab}	3.0	3.0	Side-linewidth enhancement factor
Γ	0.1 ps^{-1}	0.1 ps^{-1}	Photon decay rate
ξ_{aa}	2.7 * 10^{-9} ps^{-1}	2.7 * 10^{-9} ps^{-1}	Self-differential gain coefficient
ξ_{ab}	1.0 * 10^{-12} ps^{-1}	1.0 * 10^{-12} ps^{-1}	Side-differential gain coefficient
κ	0.02 ps^{-1}	0.02 ps^{-1}	Coupling rate
g	0.1	0.1	Threshold gain
N_{modes}	1	1	Number of active longitudinal modes
T	800 ps	800 ps	Carrier lifetime
J_{thr}	6.5 * 10^{16} s^{-1}	6.5 * 10^{16} s^{-1}	Threshold current

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