Multi-longitudinal-mode dynamics in twin-stripe lasers

M. Yousefi, D. Lenstra*

Vrije Universiteit, FEW N&S, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands
(mirvais@nat.vu.nl)

* also COBRA Research Institute, TU/e, Eindhoven

Simulations for two laterally coupled Fabry-Perot type semiconductor lasers are presented. We show a threshold reduction effect and synchronization of the longitudinal modes in case of asymmetric pumping. For symmetric pumping 50% above threshold we find chaotic oscillations with frequencies well exceeding the single-stripe relaxation oscillation frequencies.

Introduction

The need for high-speed modulation lasers for optical communications has revived the interest in laterally coupled lasers [1]. Earlier work had shown that laterally coupled semiconductor lasers would perform an on-off type of dynamics resulting in faster oscillations than the intrinsic relaxation oscillations [2]. These investigations were mostly concerned with the desire for high power by coupling the laser in arrays [3]. The subsequent work focused mainly on stable and synchronized CW-operation of the array rather than the dynamics of the system [1,3].

Currently the dynamics of two laterally coupled Fabry-Pérot type lasers has again attracted attention due to their potential application in optical communications [2,4]. A Maxwell-Bloch model for the device has been investigated [2] and the stripes were found to operate in an on-off alternating fashion such that when the right stripe is on, the left one is off and vice versa. The frequency of these oscillations was larger than the intrinsic relaxation oscillation frequency. This inspired the subsequent production of the so-called twin-stripe lasers [5] and recently the high-speed oscillations have been reported in these devices [4]. The twin-stripe lasers consist of two Fabry-Pérot type lasers that are grown on the same substrate. The distance between the stripes determines their lateral coupling strength. The two stripes have separate electrodes and can be individually addressed.

In this report we will present simulations based on a novel multimode rate equations model [6] that accounts for both coherent and incoherent coupling between the stripes. Although the stripes are electrically isolated from each other, the optical field profile within one stripe has some overlap with the gain region of the other stripe. This allows stimulated emission from the other stripe's inversion into the first stripe, which we refer to as an incoherent coupling effect. A second coupling is established by the mutual spatial and spectral overlap between the optical modes, referred to as coherent coupling. Finally, led by experimental evidence, we included a new multi-longitudinal-mode model [7]. Using this model we will demonstrate threshold reduction, complex dynamics and synchronization of the two stripes. The simulations demonstrate dynamics on a timescale significantly faster than the intrinsic relaxation oscillation timescale.

Model

In [7], each stripe is modeled as a single transverse- and multi-longitudinal-mode Fabry-Pérot type laser. The evolution of the slowly varying electrical field envelope of each

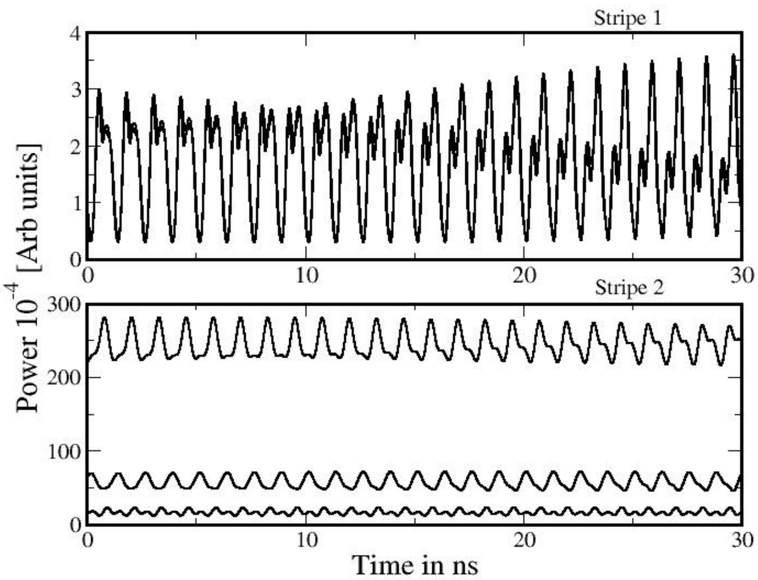

Fig. 1: Power time traces for the twin stripe laser. Note the difference in vertical scales. The arbitrary units are the same for each stripe. The stripes are detuned by several tens of GHZ, implying negligible coherent coupling; the power in stripe 1 is stimulated emission "stolen" from the inversion of stripe 2.

longitudinal mode is formulated in terms of coupled rate equations. Two inversion gratings are created in the device by assuming that each excited mode burns its own pattern in the respective inversions. Then we assign inversion moments to each longitudinal mode and account for the fact that each mode is coupled to all inversion moments, thus establishing a very rich type of multi-longitudinal, two-stripe mode competition. Finally, each of the two pump currents will induce a frequency shift of the corresponding two longitudinal-mode combs. This is accounted for by separate equations that model a linear drift of the modal frequencies with the pump current. For a more detailed discussion of the model we refer to [8].

A fourth-order Runge-Kutta method was used to integrate the system of coupled equations. Spontaneous-emission noise is not included in the results that will be presented. The parameters were chosen such that each stripe behaves as a multi longitudinal-mode Fabry-Pérot type laser. We assume three active modes in each stripe, one dominant and two side modes. The parameters are listed in table I (notation of Ref.[7]).

Results

We start by biasing one of the stripes at 50% above its threshold. This stripe will be referred to as stripe two and kept at this bias throughout the paper. To demonstrate threshold reduction, we bias the first stripe at 98% of its threshold. Fig.1 shows a time series of the modal powers of the two stripes. It is clear from fig.1 that all the modes of stripe 1 are synchronized to the signal of the dominant mode of stripe 2. Also, a low frequency envelope is present on top of the fast dynamics. The relaxation-oscillation frequency of stripe 2 at 50% above threshold is 2.25 GHz. While using the average power in stripe 1, one can calculate its relaxation-oscillation frequency to be 255 MHz.

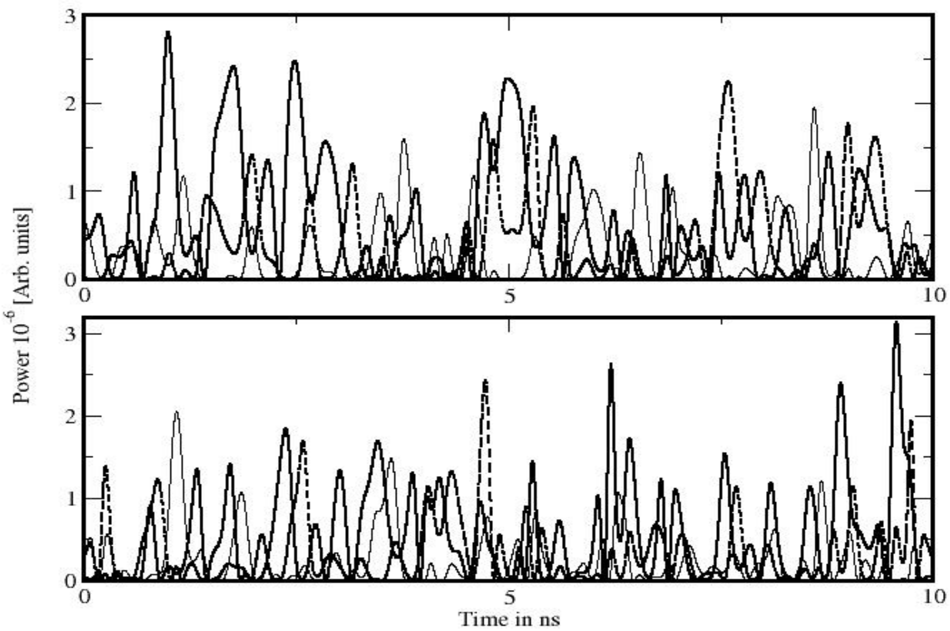

Fig. 2: Power time traces for the twin stripe laser. The stripes are slightly detuned by 10 MHz, implying strong coherent coupling.

The oscillations in fig.1, which seem to be of period-doubled type, have 1.25 ns oscillation time corresponding to a frequency of 800 MHz. This new timescale is not related to any of the conventional relaxation-oscillation frequencies.

In Fig.2 we show the power traces for a case of equal pump current (50% above threshold). In order to study both incoherent and coherent coupling, we put the detuning at 10 MHz. The effective mutual coupling strength amounts 5 ps^{-1}. The irregular dynamics indicate chaotic operation. Without coupling both stripes would exhibit stable multimode CW dynamics. The total intensities in both stripes for this case are shown in Fig.3. High-frequency oscillations up to 5 GHz are clearly seen in both stripe outputs. The qualitative explanation for these chaotic dynamics is that the system of two coherently coupled lasers is similar to two lasers with mutual optical injection. If one laser would operate CW, then the other is likely to show some type of dynamics. Therefore, quiet CW type operation of both lasers would be very unlikely indeed. The occurrence of higher modulation frequencies was also reported in [2].

Acknowledgment

The authors would like to acknowledge support by the FALCON European TMR # ERBFMRX-CT98-0223 network.

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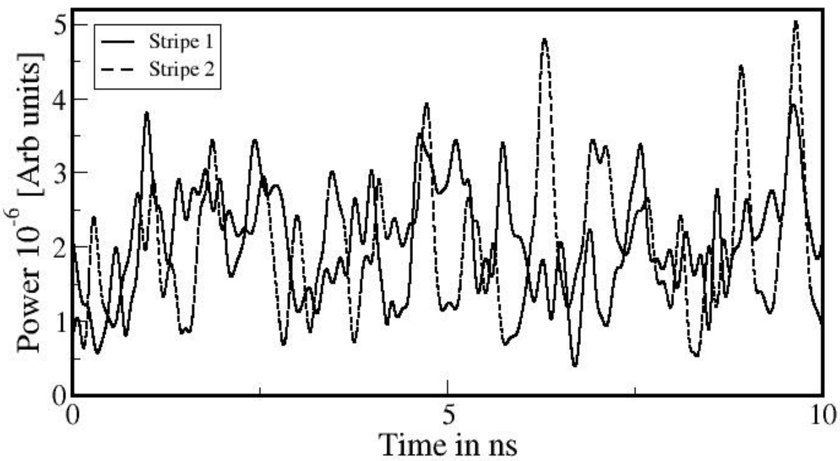

Fig. 3: The total intensities for each stripe of Fig.2 show oscillations with frequencies up to 5 GHz.

Table I: The parameters for the simulations. In view of the symmetric choice of parameters, only those for stripe 1 are shown; the parameters for stripe 2 are identical except for the ones indicated in the text. The index j labels the longitudinal modes.

Parameter	Value	Description
# of modes	3	Number of active modes
g_j	$\{0.1, 0.099, 0.098\} \cdot 10^{12}\ s^{-1}$	Threshold gain
Γ_j	$\{0.1, 0.1, 0.1\} \cdot 10^{12}\ s^{-1}$	Photon decay rate
T	10^{-9} s	Carrier-decay lifetime
J_{thr}	$1.62 \cdot 10^{17}\ s^{-1}$	Threshold current in carriers/s
$\alpha^{I:I}_j$	{5.0, 5.0, 5.0}	Self-linewidth enhancement factor
$\alpha^{I:II}_j$	{5.0, 5.0, 5.0}	Cross-linewidth enhancement factor
$\xi^{I:I}_j$	$\{1.0, 1.0, 1.0\} \cdot 10^{3}\ s^{-1}$	Self-differential gain coefficient
$\xi^{I:II}_j$	$\{1.0, 1.0, 1.0\} \cdot 10^{2}\ s^{-1}$	Cross-differential gain coefficient