Modelling of the Laser Dynamics of an (Al,In)GaN Laser Diode

1st Angela Thränhardt
Institut für Physik
Technische Universität Chemnitz
09107 Chemnitz, Germany
angela.thraenhardt@physik.tu-chemnitz.de

2nd Eduard Kuhn
Institut für Physik
Technische Universität Chemnitz
09107 Chemnitz, Germany
eduard.kuhn@physik.tu-chemnitz.de

3rd Lukas Uhlig
Institut für Physik
Technische Universität Chemnitz
09107 Chemnitz, Germany
lukas.uhlig@s2015.tu-chemnitz.de

4th Matthias Wachs
Institut für Physik
Technische Universität Chemnitz
09107 Chemnitz, Germany
matthias.wachs@physik.tu-chemnitz.de

5th Ulrich T. Schwarz
Institut für Physik
Technische Universität Chemnitz
09107 Chemnitz, Germany
ulrich.schwarz@physik.tu-chemnitz.de

***Abstract*—(Al,In)GaN laser diodes show an intricate interplay of longitudinal mode competition and mode clustering. So far, modelling of these diodes has been restricted to rate equations, necessitating the input of a variety of phenomenological parameters. Here, we perform calculations based on the semiconductor Bloch equations which offer the chance of a full many-body calculation and microscopic determination of all parameters. In the current contribution, we restrict our calculations to basic mechanisms and use phenomenological parameters for numerical reasons. Even in this simple model, we are able to reproduce the mode rolling phenomena found in measurements and gain access to parameters not accessible in a rate equation model.**

***Index Terms*—quantum well lasers, physics computing, laser theory**

I. INTRODUCTION

Following the introduction of commercially available laser diodes in 1997 [1], there has been remarkable progress in the field of blue and green (Al,In)GaN laser diodes, offering opportunities in fields as diverse as optical data storage [2], visible light communication [3] and spectroscopy [4]. The dynamic performance being of pivotal importance for many applications, phenomena such as mode competition and mode clustering [5], [6] have the potential to strongly influence the performance.

So far, modelling of the dynamics of these laser diodes has been largely restricted to the use of rate equations [7]. Although the observed phenomena can be represented in this model, no conclusion on e.g. the density distribution may be drawn, distinguishing an equilibrium from a nonequilibrium distribution. Furthermore, loss processes are modelled in a simple A-B-C model which has been shown to be inaccurate at lasing densities [8]. Rate equation models also necessitate a number of parameters to be introduced from fits to experiment, e.g. scattering times as well as loss parameters. Greater predictive power is therefore reached by using a microscopic theory where the input may be restricted to bandstructure and material quality parameters. Optical spectra may be accurately calculated for a wide variety of temperatures and carrier densities using this theory [9]; however, numerical expense limits its applicability in laser dynamics especially for the longer (ns to μs) timescales relevant for thermal effects, but also considering mode oscillation phenomena on a ns time scale. The theory thus has to be appropriately simplified, one possiblity being the precalculation of scattering rate tables [10]. Here, we present a much–simplified and thus numerically less costly version of the microscopic theory which is nevertheless able to capture the relevant aspects of laser dynamics and offers additional information as compared to the rate equation model cited above. We plan to elaborate on this approach in the future, offering a more realistic picture of the investigated laser diodes. However, the theory already models the essential phenomena observed in experiment.

II. MICROSCOPIC THEORY

In an optical device such as a laser, matter and light field are coupled by the wave equation,

$$\Delta\vec{E}(\vec{r},t) - \left(\frac{n}{c}\right)^2 \frac{\partial^2}{\partial t^2}\vec{E}(\vec{r},t) = \mu_0 \frac{\partial^2}{\partial t^2}\vec{P}(\vec{r},t), \qquad (1)$$

where $\vec{E}(\vec{r},t)$ is the electric light field and $\vec{P}(\vec{r},t)$ is the medium polarisation. n is the refractive index, c is the vacuum speed of light and μ_0 is the vacuum permeability.

The polarisation may be calculated microscopically using the semiconductor Bloch equations [11]. The microscopic polarisation couples to the electron and hole densities $n_e(\vec{k})$ and $n_h(\vec{k})$. Currently we restrict ourselves to a single particle model using only two bands and a standard scattering rate of 10 fs, having the carrier distribution relax against a Fermi distribution at lattice temperature. Spontaneous emission is included taking into account the actual degenerate carrier distribution and thus phase space filling, but using a phenomenological B coefficient. The optical field is expanded

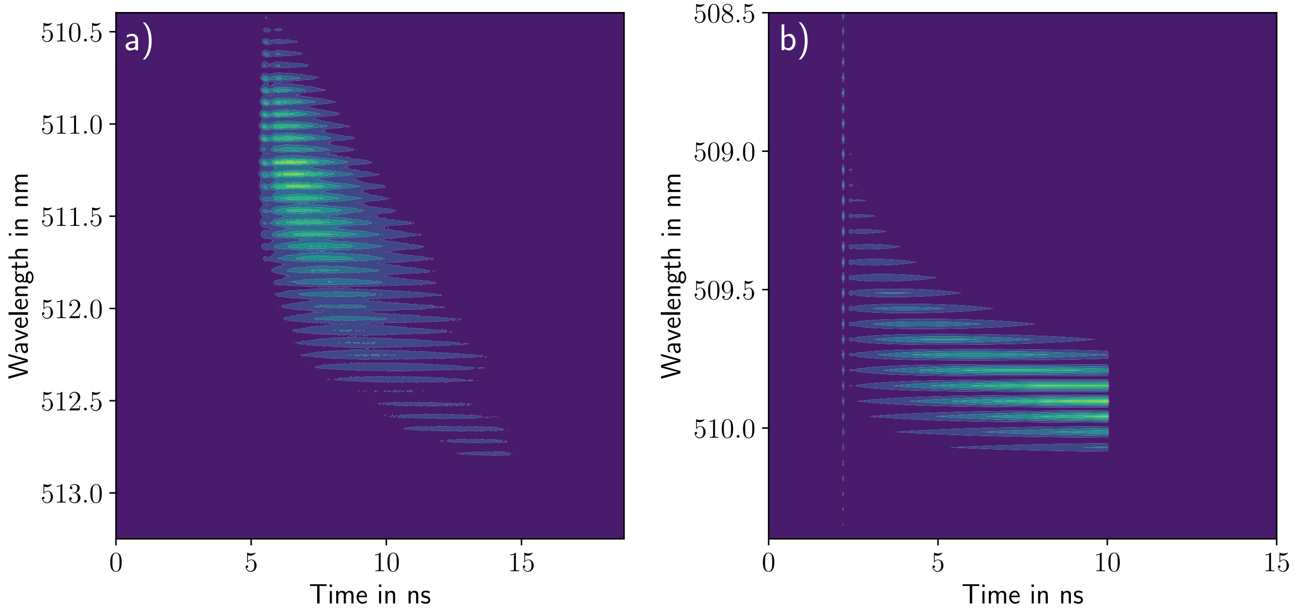

Fig. 1. Mode competition at room temperature in an (Al,In)GaN laser diode from (a) Experiment and (b) Theory.

in the appropriate modes which enter the overlap factor, determining the strength of light–matter coupling.

Even at this basic level, the theory offers access to interesting information such as the carrier distribution. Also, the calculation has the potential to be expanded into a fully microscopic model or, which is often more useful, into any intermediate state between the simple one–particle and the fully microscopic model. We will expand the model in future calculations; yet, since numerical expense often limits laser simulations, especially when very different time scales such as those of carrier scattering and thermal effects enter, will restrict ourselves to a level suited to the investigated phenomena.

III. EXPERIMENT VERSUS THEORY

The experimental details have been described before in [5]. Fig. 1 shows a comparison of experiment (a) to the calculated mode dynamics (b). Both theory and experiment show the laser modes rolling from short to longer wavelengths. Obviously, even the simple model used here is able to reproduce the basic phenomena. Looking more closely, we found that mode rolling is crucially dependent on the inhomogeneous spatial carrier distribution, originating from the low hole mobility. The reason for mode hopping being the temporal fluctuations of spontaneous emission through nonlinear cross saturation [6], we also consider it of crucial importance that phase space filling effects are correctly included in the calculation of radiative losses.

IV. CONCLUSION

Here, we apply a theory based on the semiconductor Bloch equations to the dynamics of nitride laser diodes. We find good agreement with experiment in modelling the mode rolling phenomenon. The theory offers access to a number of quantities not accesible in the rate equation model used so far, which will be discussed in detail in the conference presentation.

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