The modelling of semiconductor laser diodes

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Abstract

This paper presents a number of models for semiconductor laser diodes. The models are divided into different categories, according to the independent variables they include. The use of these different models is critically investigated and the advantages of these models are compared and discussed. A number of models are elaborated into mathematical detail and some examples are discussed.

Key words: Semiconductor laser, Modelization, Physical model, Comparative study, Static model, Dynamic model, Independent variable, Gain.

I. INTRODUCTION

Semiconductor laser diodes play an ever increasing role in a variety of systems. The application of these light sources in optical telecommunication and in optical recording systems is well known. But also in medical systems, in optical pumping of certain laser types and in metrology does the laser diode replace other light sources. It owes its popularity to its small dimensions, high power efficiency, relatively high power output, electrical modulation capability, long lifetime and low cost if produced in large volume. Different applications mean different specifications. Depending on the specific usage, a laser diode will be needed with a specific wavelength, a low threshold current, a good spectral purity (e.g. dynamic single longitudinal mode operation and/or narrow linewidth), a high modulation bandwidth, special beam characteristics or high output power. Nobody will be surprised to hear that it is difficult to reconcile all good properties in one device. Therefore many different types of laser diodes have been proposed. This number is even more extensive because of the large number of semiconductor materials, especially III-V alloys, that can be used for laser action and the highly different epitaxial
growth methods that have been developed to form the semiconductor layer stack typical for all laser diodes.

The behaviour of laser diodes is not simple. Both electronic and optical phenomena are present in the same device. The charge carrier concentrations (of both electron and holes) are high and various recombination processes need to be taken into account. The material is optically nonuniform and the propagation of waves and formation of cavity modes is complex.

Most properties of laser diodes can only be analysed by fairly complex models, and even then most models rely on approximate expressions for a number of physical dependencies, often based on experimental data. Due to the high complexity of laser diode behaviour and the large degree of uncertainty concerning a number of parameters, the modelling of these devices is mostly qualitative rather than quantitative. The main role of modelling is to acquire a better understanding of experimental laser behaviour so as to improve the design of the laser. Alternatively, new designs can be analysed prior to fabrication.

There are different types of models related to semiconductor lasers [1]. There are material models that describe the physical interactions in the semiconductor and there are process models that describe the device structure, given the fabrication sequence. Most attention is paid however (both in literature and in this paper) to models that describe the device behaviour, for given physical relationships and for a given device structure. In section II of this paper a number of general aspects of laser models will be discussed. In section III to V a number of very different device models are presented in some detail and are illustrated with examples. Finally section VI describes two material models for the gain of III-V semiconductors.

II. GENERAL ASPECTS OF LASER DIODE MODELLING

In Figure 1 the simplified geometry of a semiconductor laser diode is shown. It consists of a stack of semiconductor layers, N-type at one side of the « active » layer, P-type at the other side. The active layer needs to have a composition, such that its bandgap is smaller and its refractive index larger than that of the surrounding layers. By applying a voltage between the top metal stripe and the bottom contact a current will flow. In the active region charge carriers, both electrons and holes, will be injected and remain confined by the action of the heterojunctions. Therefore high concentrations of charge will be present, leading to efficient recombination. In a limited wavelength range, absorption will become less probable than stimulated recombination and therefore the active layer will exhibit gain.

A cavity is formed by confining light in three dimensions. In the transverse or x-direction (see Fig. 1), a relatively large index step exists at both sides of the active layer, which means that it forms a slab waveguide that can guide light. In the longitudinal or z-direction the structure is terminated by cleaved facets, with or without dielectric coatings, that provide reflection back into the device. In the lateral or y-direction, the situation is far more complex. In the simple situation as shown in the Figure, there is no confinement or guiding mechanism. However the gain that is present under the stripe, can be sufficiently high, such that it compensates for diffraction loss. This diffraction loss is relatively large because the carrier injection profile causes a depression of the refractive index at the gain maximum, which is an anti-guiding effect. Numerous designs have been proposed to incorporate a lateral waveguiding effect in the laser structure, either by having a real refractive index step in lateral direction or by having a lateral geometry variation that induces a lateral change of the effective index seen by the transverse mode.

The physical interactions are schematically shown in Figure 2. The potential distribution, carrier concentrations and current densities are linked through Poisson’s equation, current equations and continuity equations. The latter need to take into account absorption and recombination phenomena. That means that the net gain (or loss) and also the power density of the optical fields appear in these equations. The net gain (and also the refractive index change) depend on the carrier density and are needed to describe the wave propagation and the cavity resonance. In some models temperature effects are taken into account. Both electrical and optical heat dissipation are then introduced into a heat diffusion