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Trends in modelling of single frequency laser diodes

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1. Introduction

Modelling of single frequency laser diodes and in particular of distributed feedback (DFB) laser diodes has been going on for over ten years now. At an early stage, it already became clear that several aspects of the behaviour of DFB lasers are related to an axially non-uniform electron density. Therefore most of the developed models are longitudinal models, in which all variations in the longitudinal direction are taken into account in a self-consistent way [1-3]. The wave equation is thereby reduced to a set of coupled wave equations through the introduction of an effective (complex and carrier density dependent) refractive index and a (constant) confinement factor. Carrier density variations in the lateral and transverse directions are usually ignored in this approach.

Many undesired aspects of the behaviour of DFB lasers, such as linewidth rebroadening and the side mode suppression degradation at high powers, have been explained using longitudinal models. The degradation of the side mode suppression e.g. was found to be caused by too large axial variations in the optical power giving too large axial variations in the electron density. Such large variations are mainly present in lasers with strong distributed feedback (or deep gratings). Most of the currently fabricated lasers now have a weaker feedback and hence a stable single mode behaviour.

Much effort is now concentrated on the optimisation of the lasers for high speed operation, use in analog communications, short pulse generation, etc.. The optimisation is however still largely qualitative. The reason is that longitudinal models require too much calculation time to use them in optimisation software. The optimisation is also hampered by a difference between the set of growth and process parameters and the set of laser model parameters. Knowledge of the optimum model parameters can therefore not easily be translated into optimum growth and process parameters. The previous two factors have given rise to a significant effort towards simpler laser models and towards parameter extraction from measurements. The latter is one possible method to establish the relation between model parameters and growth and process parameters.

2. Towards simpler models: rate equations that are also accurate for DFB lasers

Longitudinal models have been used with success in the explanation and the optimisation of the behaviour of DFB laser diodes. Nevertheless, there is a growing awareness that their numerical complexity makes them less attractive for use as submodule in larger software environments such as system or optimisation models. Another disadvantage of such models is that they don't provide physical insight (a key factor in the design) to the user. It is only by comparing numerical results obtained for different structures, a time consuming process, that such insight develops when using longitudinal models.

For the above reasons there is a trend towards simpler, lumped DFB laser models [4-6]. Such models, based on rate equations that describe the evolution in time of the number of photons in a mode, the number of electrons in the cavity and the frequency of each mode, already exist as long as the concept of laser itself. The traditional rate equations however don't include the effects of a non-uniformity in the carrier density and therefore don't give a very accurate description of the behaviour of DFB lasers.

The rate equation models that are currently being developed are based on an additional equation for the non-uniform part of the carrier density. Also new equations for the average photon density and the frequency variation, taking into account the non-uniform carrier density, are derived (e.g. from the coupled wave equations). The longitudinal variations are assumed to be similar for carrier and photon density. They are typically included in the equations through 4 additional quantities, among which the variance and the skewness of the longitudinal power distribution.

The new rate equations have been shown to give accurate numbers for characteristics such as the chirp or the harmonic distortion which are strongly influenced by spatial carrier density variations. Calculations with the new rate equation models have given identical results as calculations with longitudinal models for these characteristics. This is illustrated in Fig. 1, which shows the chirp caused by the axial variations of the carrier density obtained both with a longitudinal model and a rate equation model. The chirp is the modulation of the optical frequency that accompanies the intensity modulation in laser diodes.

3. Towards better agreement with measurements: parameter extraction

There are also efforts to introduce a feedback from measurements on fabricated devices in the design process or, in other words, to compare fabricated devices with the design specifications. Together with accurate design tools, this will allow a much more efficient optimisation of fabrication processes. To this end, the physical parameters of the fabricated component must be extracted from different measurements on the component.

Several possibilities to do this extraction have been explored recently. The recombination parameters e.g. can be determined from measurements of the modulation bandwidth below the threshold current [7]. The carrier dynamics are not influenced by stimulated emission and they obey a first order equation (with a time constant determined by the recombination parameters) in that case. Different gain parameters can be derived from the modulation or RIN spectra measured as a function of the current above the threshold current. In this case, the interaction of photon and carrier density through stimulated emission results in a resonance. The frequency and damping of that resonance depend on the gain parameters.

It has been recognised that the optical spectrum of a DFB laser diode, measured below threshold, has a lot of structure and is notably different for different laser structures [8]. Fitting of an analytical expression to that spectrum therefore allows to derive values for several laser parameters and in particular for the grating parameters (i.e. grating phases at the facets, grating depth, etc.). This technique of parameter extraction is illustrated in Fig. 2 for a DFB laser with uniform grating and cleaved facets. In addition to the grating parameters also the wavelength dependence of refractive index and gain follow from the fitting. Because of the complicated expression for the spectrum, the fitting requires numerical optimisation routines applied to a programmed expression for the spectrum.

Ideas to bring several or all laser characteristics into one large tool for the extraction of all laser parameters are being investigated in the framework of the European ACTS project BLISS. Rate equation models with a same accuracy, but a significantly smaller calculation time than longitudinal models are an important factor in the development of such a tool.

3. Conclusion

The direction in laser diode modelling is mainly aimed at making possible a more efficient design and optimisation of DFB lasers. Links with the fabrication (through parameter extraction) and with system design (through the development of simple models for use in system models) are thereby considered more and more.

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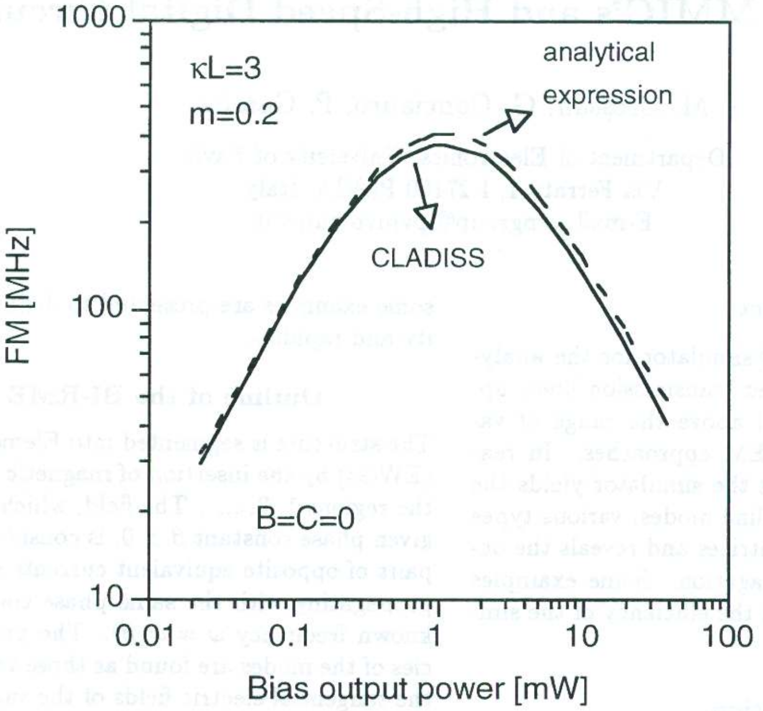

Fig. 1: Chirp caused by axial carrier density variations as a function of the bias output power for a AR-coated DFB laser and for an optical modulation depth of 20%, obtained with a longitudinal model (—) and with a rate equation model (- - -).

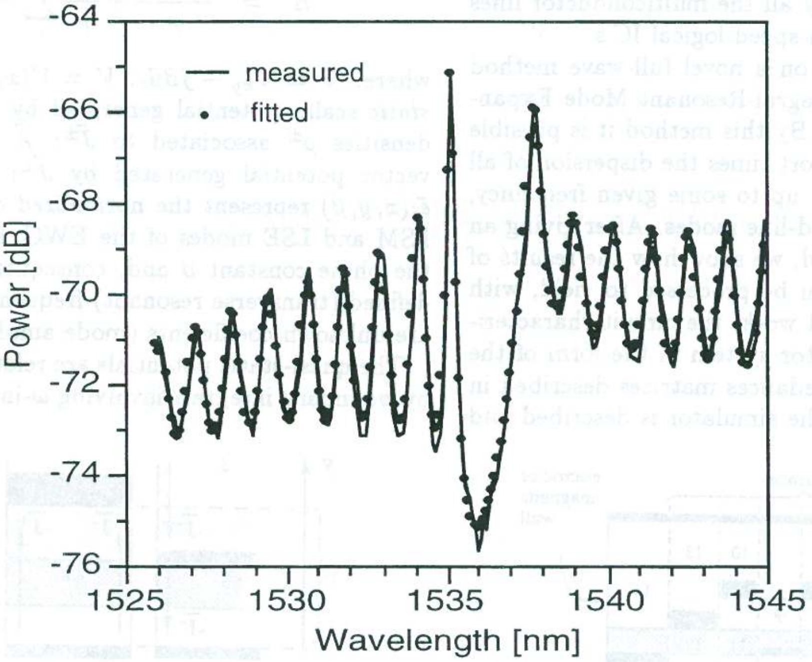

Fig. 2: Measured and fitted optical spectrum of a DFB laser with cleaved facets.