Self-consistent simulation of high-brightness diode lasers with external optical feedback

M.A. Helal[*], S. Bull, S.N. Kaunga-Nyirenda, J.J. Lim and E.C. Larkins

Photonic and RF Engineering Laboratory, Advanced Optics Group, Faculty of Engineering,
University of Nottingham, University Park, Nottingham, NG7 2RD, U.K. (*eexmahel1@nottingham.ac.uk)

Abstract—**This paper presents a model for simulating the impact of external optical feedback on large-optical cavity high-brightness diode lasers. The simulations are performed with our 2.5D simulation tool for high-brightness laser diodes. The external cavity is modelled using commercial coherent ray tracing software. We consider the impact of the optical feedback on the excitation of amplified spontaneous emission in the parasitic vertical modes.**

Index Terms—**Diode Lasers, Optical Feedback, Brightness, Ray Tracing, External Cavity**

I. Introduction

HIGH-power lasers are addressing an increasing number of applications. In order for them to offer competitive solutions, they not only need to produce a high output power, but also need high power conversion efficiency and excellent beam quality. In order to produce a high output power, the laser needs a large volume of gain material and a wide output facet to prevent facet degradation and catastrophic optical mirror damage (COMD). The initial design optimisation and performance evaluation of high-brightness laser diodes is usually carried out without any feedback from an external optical system. In practise, however, they are almost always placed in a larger optical system, whereby even simple applications use multiple optical components to collimate, shape and focus the output beam - all of which can introduce optical feedback. In more complex systems, external feedback may be used to improve the beam quality through spatial mode filtering [1], wavelength stabilisation [2] or even phase locking for coherent beam combining (CBC) [3, 4]. As the output power of laser diodes continues to increase, even small amounts of unintentional feedback can affect the performance and even the degradation/failure of the laser [5]. Furthermore, large optical cavity (LOC) structures are commonly used in high-power laser diodes to reduce the vertical far-field divergence and simplify optical coupling. These LOC structures support multiple vertical modes, but (in the absence of external feedback) lasing is limited to the mode which reaches threshold first (usually the fundamental mode). When operated in a system with external feedback, however, back coupling to higher-order modes can cause them to lase. Even if the external feedback does not allow these modes to reach threshold, the additional stimulated emission and free-carrier absorption processes can reduce the laser's efficiency and cause self-heating. Several groups [1, 4] have modelled external cavity laser diodes where optical feedback was used positively (e.g. beam quality improvement and phase locking

for CBC) but much less focus has been given to modelling the negative impact of external optical feedback.

II. Laser Diode Simulation

The laser diode is simulated with *Speclase,* our 2.5D multiple wavelength simulation tool [6]. This tool solves the optical propagation (x-z) using a 2D wide-angle finite-difference beam propagation (2D WA-FD-BPM) algorithm. It also solves the transverse (x-y) electrical and thermal slices along the cavity. The simulation tool is modified to include multiple vertical modes and incoherent coupling to commercial coherent ray tracing software [7]. The modal confinement factors, propagation constants and free-carrier absorption coupling are calculated for all vertical modes. Multiple wavelength operation is modelled by including spontaneous emission coupling and the spectral dependence of the gain and refractive index. The model also includes non-linear effects (e.g. thermal lensing, spatial hole burning), which are common in high-brightness lasers.

III. Coupling of External Cavity Model to Speclase

In this work, commercial optical modelling package (*Optic Studio)* is used to model the beam propagation through the external cavity. Our goal is to convert the beam data produced by *Speclase*, in the form of near-field (NF) and far-field (FF), into ray data. These ray data are used to configure the laser as a source within *Optic Studio*. *Speclase* propagates the optical fields between the rear and the front facet using 2D WA-FD-BPM. At the front facet, part of the power within the modes will reflect off the facet, while the rest will be transmitted through. The spatial superposition of transmitted powers, of all the modes, forms the near-field of the transmitted beam. Because the laser is utilised in an external cavity, then a part of the transmitted beam will reflect off of successive surfaces in the external cavity and come back impinging on the facet. In order to study the effect of these reflections, the transmittance and reflections off of optics elements needs to be simulated. Within *Optic Studio*, the rays of a laser source are defined with the following attributes: launching coordinates and intensity; which are obtained from the output NF and direction cosines; which are obtained from the output FF. Due to the astigmatic nature of the laser, the output rays will originate from two virtual line sources, rather than a single virtual point source for a non-astigmatic light source. The output rays have to intersect with these two line sources; one for vertical divergence and the other for horizontal divergence. The longitudinal position of these line sources was obtained through back-tracing the rays

while the transverse position was obtained by finding the first-moment. Next, the rays returning to the laser facet were converted into optical fields, taking the phases of the rays into account. Then the proportion coupled to each vertical mode is determined, using the overlap integral. Finally, the vertical modes, containing the amount of power incoherently-coupled from the external cavity and the internally reflected fields, are propagated by *Speclase* inside the laser cavity using a Fox-Li approach. This whole process is repeated until convergence.
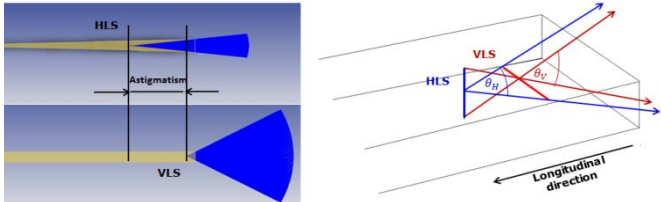

Fig. 1: Top & side view of astigmatic laser source showing horizontal and vertical line sources (left). Converting 2D angular distribution into 3D angular ray distribution (right).

IV. RESULTS

For this paper, we simulated a triple QW 975 nm DBR tapered laser, placed in a simple external cavity. The tapered laser is comprised of a 3mm RW section, of which 1 mm is an un-pumped DBR, and a 3mm tapered section with a taper angle of 6° and an output aperture of ~ 350μm. The front facet reflectivity is 0.01% while rear facet DBR has an effective reflectivity of ~31%. The external cavity optics is comprised of AR-coated slow- and fast-axis collimating lenses and an uncoated fibre with a reflectivity ~5%, as illustrated in Figure 2. By turning on the ray splitting and scattering in *Optic Studio,* we are able to simulate stray reflections off the optics.
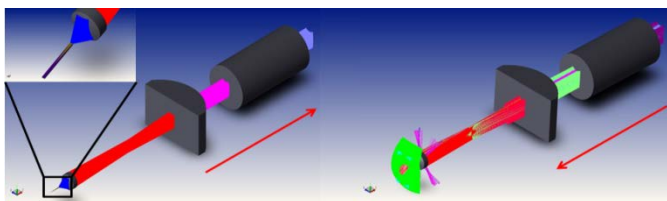

Fig. 2: External cavity setup used in the simulation. Rays splitting and scattering turned off (left). Rays splitting and scattering turned on (right).

The results of external cavity simulation are compared to that of the stand-alone simulation. When the laser diode is placed in an external cavity, the back reflections cause the higher-order vertical modes to be excited and to propagate in the laser cavity. This propagation makes these modes compete for gain and the converged results are depicted in Figure 3. The excitation and propagation of higher-order modes leads to performance degradation in the form of low output power [5], increased internal losses, increased internal heating and increased NF modulation depth, which is consistent with that observed experimentally by Leonhäuser *et al.*[8].
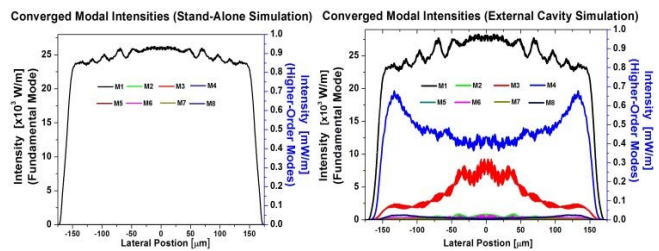

Fig. 3: Converged lateral intensity profiles of all vertical modes. Stand-alone simulations (left). External cavity simulations (right).

V. CONCLUSIONS, CHALLENGES AND FUTURE WORK

External optical feedback cannot be ignored, as it impacts on laser performance. The propagation of the excited higher-order modes increases the free-carrier absorption causing self-heating which eventually causes degradation of the output power, efficiency and beam quality. The next step is to analyse the results by investigating and quantifying this impact on the output beam quality and efficiency. This will be used to optimise the designs of high-brightness lasers to supress and attenuate the propagation of parasitic modes [9]. The challenge for now is to upgrade this model to include coherent coupling between the laser simulator and the external cavity modelling package. This will allow us model more complex systems (e.g. with multiple emitters).

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