# Travelling wave analysis of high pulsed power long-wavelength asymmetric-waveguide short-cavity laser diodes with a bulk active layer.

Eugene A. Avrutin[1*], Boris S. Ryvkin[2,3]

[1] Dept of Electronic Engineering, University of York YO10 4LE, UK ([*]eugene.avrutin@york.ac.uk)
[2] A.F. Ioffe Physico-Technical Institute, St. Peterbsurg 194021, Russia
[3] Circuits and Systems Research Unit, University of Oulu, 90014, Finland,

***Abstract* — An effective one-dimensional travelling wave model is used to analyse the performance of a short-cavity asymmetric-waveguide high pulsed power laser diodes. The effect of longitudinal inhomogeneity is proven to be modest for practical laser designs.**

## I. Introduction and Background

HIGH power broad area pulsed diode lasers operating in the eye-safe wavelength range (λ= 1.4-1.7 µm) are indispensable for applications including medical instrumentation and range finding / LIDAR systems. The dominant issue in designing these pulsed sources, in which self-heating is not expected to be an issue, is increasing the output efficiency, which typically involves minimizing the internal losses $\alpha_{in}$, both built-in ones and those arising at high injection levels. The main source of $\alpha_{in}$ increase has been identified as accumulation of carriers in the optical confinement layer (OCL) of the laser structure and free carrier absorption (FCA) by those carriers (mainly holes) at high current i. In pulsed lasers at room temperature the dominant reasons of this carrier accumulation are, firstly, the current flow itself and, secondly, two-photon absorption (TPA) –the *indirect* effect of TPA (see [1]-[3] and references therein). The *direct* TPA effect also contributes to $\alpha_{in}$ but has been predicted to be weaker [1]-[3] and is also partly offset by recapture of TPA-created carriers into the active layer. The relative importance of the absorption mechanisms above has been shown to depend critically on the laser design. In lasers with approximately symmetric, broad waveguides and the active layer (AL) near mode peak, the FCA by current-induced carriers clearly dominates whereas the TPA effects, both direct and indirect, are negligible [1][4]. In a laser design where current-induced carrier accumulation is suppressed, however, the situation becomes different. Such a design was proposed and realized in a series of our recent papers [3][5]. It involves a combination of, firstly, a double-asymmetric waveguide structure with the AL near the *p*-cladding [6],[7] to minimize the effect of carrier accumulation in the (virtually absent) *p*-side of the OCL; secondly, *n*-doping of the *n*-side of the OCL sufficiently high to decrease carrier accumulation therein; and, thirdly, a relatively short ($L$=1-2 mm) cavity to increase the output efficiency additionally by increasing the output loss $\alpha_{out}$ compared to $\alpha_{in}$. The short laser needs a moderately thick ($d$=600-800 Å; bulk, in our case) AL to avoid excessive threshold increase. Theoretical analysis so far used a lumped model, solving the transcendental equation for the power $P(i)$:

$$P(i)=\eta_i\frac{\hbar\omega}{e}\frac{\alpha_{out}}{\alpha_{out}+\alpha_{in}(i,P(i))}\left(i-i_{th}^{eff}(i)\right) \quad (1)$$

with the different current- and power-dependent contributions to $\alpha_{in}(i,P(i))$ calculated self-consistently [2][3][5]. Good agreement with experiments (with some parameters fitted within the relatively broad limits quoted in the literature) was reached [5]; however, the accuracy of the lumped approach is not entirely obvious *a priori*. Indeed, firstly, the bulk AL leads to substantial $\alpha_{in}$ (~5-10 cm$^{-1}$), meaning that Longitudinal Spatial Hole Burning (LSHB [8], whose effect on output $P$ increases with $\alpha_{in}L$ [9]) might be of some significance despite the relatively small $L$. Moreover, with the current-induced carrier accumulation suppressed as discussed above, the main mechanism of $\alpha_{in}$ increase at high $i$ is the (mainly indirect) TPA effect, which is itself substantially longitudinally inhomogeneous due to the asymmetric facet reflectances. Finally, the TPA effects (particularly the direct one) respond to fast power oscillations in the longitudinally multimode laser. The aim of this study is to quantify the effects of spatial nonuniformity and fluctuations of power on the performance of lasers of this type and verify the validity of the lumped model.

## II. Model and simulations.

The model used is a modification of the travelling-wave model LasTiDom (see e.g. [7]), which involves analysing the complex amplitudes of the forward ($E_F$) and reverse ($E_R$) propagating waves in one (longitudinal $z$) spatial dimension plus time $t$:

$$\pm\frac{\partial E_{F,R}}{\partial z}+\frac{1}{v_g}\frac{\partial E_{F,R}}{\partial t}=\frac{1}{2}\left((\Gamma\hat{g}-a_{in})E_{F,R}+j\Gamma g''E_{F,R}\right)+F_{sp}(z,t) \quad (2)$$

Here, as usual $\hat{g}=\hat{g}(z,t)$ and $a_{in}=a_{in}(z,t)$ stand for the optical gain (frequency dependent hence the operator nature of $\hat{g}$) and the internal absorption respectively, $g''E_{F,R}$ is the self phase modulation term, $F_{sp}$ is the noise source. The equation is solved as usual in a system with the distributed rate equation for the active layer carrier density $N(z,t)$. The focus of the current work is systematic inclusion of the current- and power-dependent contributions to $\alpha_{in}$ in addition to the built-in term $\alpha_{in}^{(b-i)}$:

$$a_{in}=\alpha_{in}^{(b-i)}+\alpha_{AL}^{(FC)}(z,t)+\alpha_{j}^{(FC)}(t)+\alpha_{TPA}^{(FC)}(z,t)+\alpha_{TPA}^{(mod)}(z,t) \quad (3)$$

The terms in (1)(3) are ($z,t$)-dependent versions of those used in [3]. The FCA in the AL $\alpha_{AL}^{(\mathrm{FC})}(z,t)$ was calculated from the AL carrier density $N(z,t)$. The direct TPA effect $\alpha_{TPA}^{(\mathrm{mod})}(z,t)$ was evaluated using the ($z,t$)-dependent version of Eq. (2) of [2]:

$$\alpha_{TPA}^{(\mathrm{mod})}(z,t)=\beta_2^{(OCL)}b_{TPA}S(z,t) \tag{4}$$

where $S(z,t)=\left|E_F^2(z,t)\right|+\left|E_R^2(z,t)\right|$ is the local photon density, $\beta_2^{(OCL)}$ is the TPA coefficient of the OCL material, and the coefficient $b_{TPA}$ is determined by the transverse modal profile [2]. The calculation of the free carrier losses due to the current flow $\alpha_j^{(\mathrm{FC})}(t)$ and due to the indirect TPA effect $\alpha_{TPA}^{(\mathrm{FC})}(z,t)$, strictly speaking, requires time-dependent analysis of carrier flow in the vertical direction $x$, which would mean 2D+time simulations. However in the quasi-steady-state regime of interest here, $\alpha_j^{(\mathrm{FC})}$ can be calculated directly from the steady-state analysis [2][3], whereas $\alpha_{TPA}^{(\mathrm{FC})}(z,t)$ sees only small oscillations around the steady state value, driven by the random oscillations of $S(z,t)$ in the longitudinally multimode laser. Thus, we represent the kinetics of TPA-induced carriers by a single characteristic time $\tau_x$ that accounts for their recombination and vertical transport to the AL:

$$\frac{\partial\alpha_{TPA}^{(\mathrm{FC})}(z,t)}{\partial t}=\frac{1}{\tau_x}\left(B_{TPA}^{(FC)}S^2(z,t)-\alpha_{TPA}^{(\mathrm{FC})}(z,t)\right) \tag{5}$$

The proportionality coefficient $B_{TPA}^{(FC)}$ (and the time $\tau_x$) are determined from the *steady state* analysis of TPA-induced carrier distribution $N_{OCL}(x)$ [2][3], and so the *dynamic* model is kept one-dimensional. The parameters common with the lumped model were taken from [3], whereas the gain spectral width and peak wavelength shift with carrier density were adapted from [10]. The output power was calculated by averaging over the second half of a 20-ns long pulse.

Fig.1 shows the extent of LSHB: the profiles of $P(z)\propto S(z)$ (time-averaged) and $N(z)$. The functional form of $P(z)$ curves is somewhat different from the profiles caused by LSHB with $a_{in}\neq a_{in}(z)$ [9], but the degree of nonuniformity is similar.

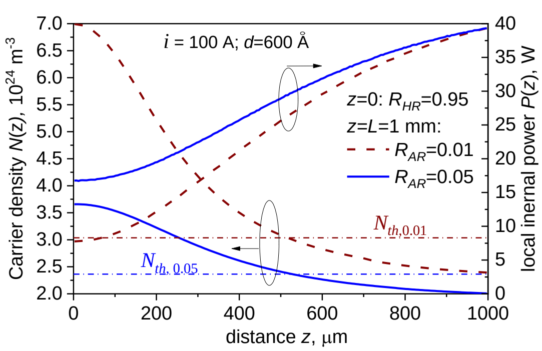


*Fig. 1. Time-averaged P(z) and N(z) distributions along the 1 mm long cavity*

Calculated current-power dependences are shown in Fig. 2, alongside those given by the lumped model of Eq. (1). With the parameter values studied, the significance of the spatial nonuniformity, while not vanishingly small, is rather modest, of the order of a few per cent at $i$=100 A, particularly in the case of the relatively high output mirror reflectance of $R_{AR}$=0.05 as in [5]. In the case of the lower $R_{AR}$=0.01, the difference between the models, although still modest, is greater (as can be expected). Thus, while a distributed model may be necessary for analysing very small $R_{AR}$ (and large $L$) cases, the lumped model may be considered validated for a broad range of structures of practical importance.

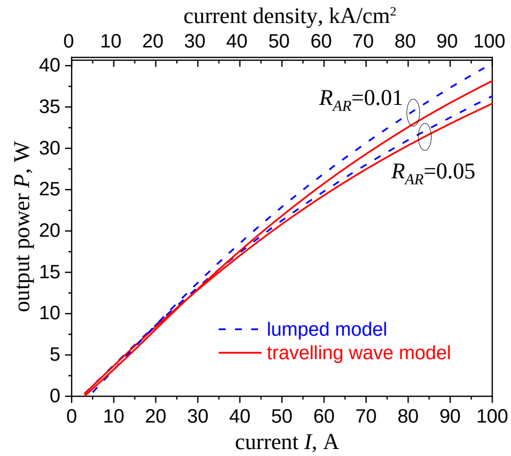


*Figure 2. Output curves simulated with different models.*

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