Evaluating Two-Photon Absorption Effects on Pulsed High-Power Laser Operation

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Abstract – **The influence of two-photon absorption (2PA) on the pulse power saturation of GaAs-based lasers is investigated and compared to other loss mechanisms. Our numerical model self-consistently solves the drift-diffusion equations and the waveguide equations for a broad-area Fabry-Perot laser diode. Using common absorption parameters, we find that 2PA makes a much smaller contribution to the power saturation than free-carrier absorption (FCA). FCA is mainly caused by carrier leakage from the quantum wells while 2PA-generated carriers are of minor importance.**

***Index Terms*— semiconductor lasers, numerical analysis**

Two-photon absorption (2PA) in GaAs-based lasers receives increasing attention in recent years.[1] 2PA generates an electron-hole pair by absorbing two photons at once, it therefore rises with the square of the photon density, and it is most relevant in the waveguide layers. Based on previous laser simulations, 2PA may be considered one of the main mechanisms responsible for pulse power saturation at high lasing power (> 10 W), in absence of self-heating and catastrophic optical damage.

Dogan et al.[2] reproduced the measured pulse power vs. current (PI) sub-linearity by including 2PA as well as free-carrier absorption (FCA) within a one-dimensional traveling-wave optical model. This secondary FCA effect is caused by 2PA-generated carriers. They find that the secondary FCA exceeds the primary 2PA for laser powers near 30W and above. However, their model ignores carrier transport effects such as carrier leakage from the active layer and it employs the free-carrier recombination lifetime within the waveguide layers as fit parameter to find agreement with measurements. Carrier leakage was previously identified as a root cause of the pulse power saturation of GaAs-based lasers.[3] More recently, Avrutin and Ryvkin[4] included some carrier transport effects, but no recombination, by solving the vertical carrier diffusion equation within the waveguide analytically. With the exception of strongly asymmetric waveguide designs, they find that both the primary and secondary 2PA effect are smaller than FCA caused by injected carriers, even for output powers near 80W. However, carrier leakage from the active layer is still not considered in this model. Most recently, Zeghuzi et al.[5] employed a two-dimensional multi-mode traveling-wave model to reproduce the measured pulse power sub-linearity. But carrier transport effects are included only in lateral direction, inside the active layer. Vertical carrier leakage from the active layer is ignored as well as free carrier accumulation in the waveguide due to 2PA. The authors identified a significant primary 2PA influence but had to include a very high gain compression factor of 18×10^{-17} cm^3 as fit parameter to match the measured power saturation.

Since none of these previous modeling approaches includes all discussed saturation processes simultaneously, we here combine all those mechanisms self-consistently within the framework of the PICS3D laser simulation software, employing common material parameters.[6] Our model solves the semiconductor drift-diffusion equations as well as the optical equations in vertical and longitudinal direction for a broad-area Fabry-Perot laser. 2PA-generated carriers as well as injected carriers follow the same transport mechanisms and both contribute to FCA.

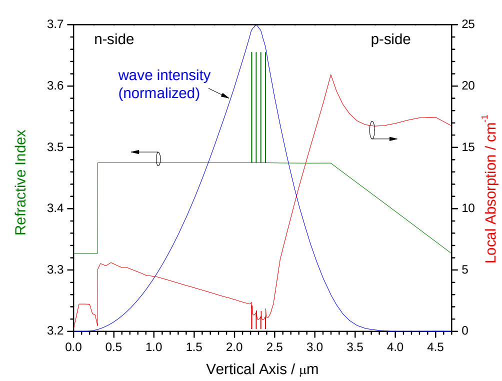

Fig. 1: Vertical profiles of refractive index, wave intensity (normalized), and local absorption.

For comparison, we investigate the same laser example as previous authors,[2,7] featuring an InGaAs/GaAs multi-quantum well (MQW) active region that is sandwiched between GaAs waveguide layers and AlGaAs cladding layers. The vertical index profile of the waveguide region and the optical intensity are plotted in Fig. 1. The guided laser mode is well confined within the GaAs waveguide layer, so that an uniform 2PA coefficient of $\beta = 26$ cm/GW can be employed.[1] The FCA cross-section is 12×10^{-18} cm^2

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for free holes and 4×10^{-18} cm^2 for free electrons, as used by the other authors.[2,7] However, we neglect 2PA and FCA within the QWs because bulk properties are not applicable here and reliable QW data are unavailable. The local absorption profile at I = 240 A pump current is shown in Fig. 1 and reveals strong free-carrier absorption within the p-side waveguide layer which is mainly triggered by electron leakage. Some of the leaking electrons accumulate in the p-side waveguide and attract holes which cause strong FCA. Additional electron-hole pairs are generated by two-photon absorption and also cause some FCA. Figure 2 compares the contributions from different absorption mechanisms. FCA by holes clearly dominates, including a small contribution from 2PA-generated carriers. But the primary 2PA is less important, as predicted by Avrutin and Ryvkin.[4]

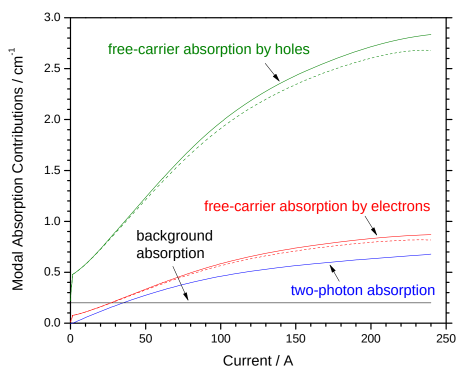

Fig. 2: Contributions of the different absorption mechanisms to the modal optical loss vs. current. Solid lines: full model. Dashed lines: free-carrier absorption without two-photon absorption.

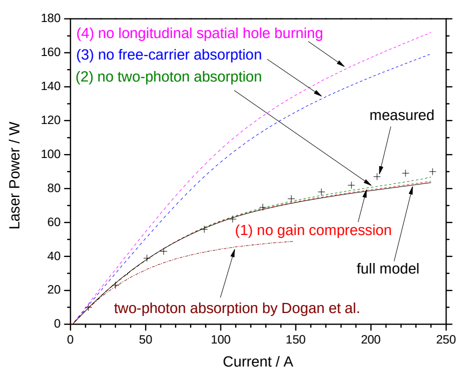

Fig. 3: Laser power vs. current as measured (+++) and as simulated with the full model (solid line). The dashed lines show the simulation results after subsequent removal of key mechanisms from the model.

Without any parameter fitting, our simulated PI characteristic exhibits excellent agreement with the measurement (Fig. 3). A somewhat lower power is calculated when bulk absorption coefficients are also applied to the quantum wells.[8] In the following, we investigate the influence of key processes on the power saturation by their subsequent removal from the model. First, gain compression is removed in Fig. 3 which shows a negligible effect when using the common gain compression factor of 10^{-17} cm^3.[1] This phenomenological factor is often employed as fit parameter to find agreement with measurements so that other authors end up with much larger numbers to compensate for power overestimations in their model. Next, two-photon absorption is also removed from the model revealing a surprisingly small 2PA influence in Fig. 3 (free-carrier absorption by 2PA-generated carriers is also missing in this case). Despite our larger 2PA coefficient β, we cannot confirm the strong 2PA influence proposed by Dogan et al. for the same laser using a somewhat smaller β = 15 cm/GW.[2] Their 2PA model leads to a significantly lower output power in our simulation (dash-dot line in Fig. 3) because it assumes that FCA by 2PA-generated carriers rises with the third power of the photon density. This assumption postulates that three photons are simultaneously involved, which is incorrect as 2PA and FCA are separate processes. However, complete removal of FCA from our model results in a much higher laser power in Fig. 3. This large FCA influence confirms earlier investigations that observed a strong increase of the internal absorption with rising pulse current.[9,10] Finally, longitudinal spatial hole burning (LSHB) is removed by enforcing longitudinally uniform carrier density and gain, which produces a somewhat higher power in Fig. 3. The remaining sub-linearity of the top curve in Fig. 3 is attributed to carrier leakage. A linear extrapolation of that curve would give about 260 W at 240 A, which is 90 W above the top data point in Fig. 3. Thus, leakage constitutes the strongest loss mechanism at 240 A, followed by free-carrier absorption which produces a drop of 73 W and LSHB with a drop of 13 W. 2PA causes only 2 W power drop and gain compression only 1 W.

In summary, carrier leakage and subsequent free-carrier absorption are the main reason for the pulse power saturation of this laser while two-photon absorption and gain compression are negligible.

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