Numerical models for the analysis of thermal phenomena in nitride edge-emitting lasers and their one-dimensional arrays

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***Abstract*— We present commonly used numerical models for the thermal analysis of edge-emitting semiconductor lasers and their one-dimensional arrays. The modeling approaches are examined in terms of the simplifications they employ, and their results are compared. As a case study, we investigate a nitride-based, green-emitting edge-emitting laser and a one-dimensional array composed of such devices. Our findings demonstrate that well-designed simplified simulations can yield not only qualitatively but also quantitatively accurate results, thus providing a viable alternative to computationally intensive full 3D thermal simulations.**

Keywords— nitride edge-emitting lasers, thermal analysis, computer simulations, numerical models

I. Introduction

Semiconductor lasers are extensively used in modern technologies, with wide-ranging applications in consumer electronics, industry, telecommunications, and medicine. The accurate design of these devices requires a comprehensive understanding of the underlying physical phenomena. However, experimental investigations are often associated with high costs, long development times, and various technological constraints. As a result, numerical simulations have become an indispensable tool for researchers engaged in the design and optimization of such devices.

Since temperature has a direct impact on the performance, lifetime, and stability of semiconductor lasers, thermal analysis is a critical aspect, especially for high-power devices [1–3] and those based on gallium nitride (GaN). Due to the structural complexity of these devices, analytical approaches are generally inadequate [4], and more accurate predictions require numerical modeling. Various types of models are used depending on the level of detail, including thermal models with either localized or distributed heat sources [1,2], electro-thermal models [3], and, in the most advanced cases, opto-electro-thermal models [3]. These models may be self-consistent, accounting for both the temperature dependence of material properties and the coupling between electrical and thermal effects. In addition, the dimensionality of the model, which can range from one-dimensional (1D) [4,11] to full three-dimensional (3D) simulations [1–3], significantly affects the trade-off between computational cost and accuracy.

In this study, three modeling approaches are compared: a two-dimensional purely thermal model (2D Ts), a two-dimensional electro-thermal model (2D TE), and a three-dimensional electro-thermal model (3D TE). All models incorporate temperature-dependent material parameters. In addition, a hybrid model (3D Tr) is proposed, in which the heat source distribution within the 3D geometry is derived from the results of the 2D TE model. This approach is motivated by the specific geometric characteristics of the simulated structures.

The results demonstrate that the hybrid approach offers accuracy comparable to that of the full 3D model while substantially reducing computational cost. The 2D models provide reliable qualitative insights, and their quantitative accuracy can be enhanced through the use of appropriate correction factors. Due to their computational efficiency and speed, such simplified models are commonly employed in practice. The comparative analysis was performed using a GaN-based green edge-emitting laser (see Fig. 1) and a one-dimensional array consisting of ten such devices.

II. Numerical model

The simulations were performed using proprietary software developed by the Photonics Group at the Institute of Physics, Lodz University of Technology. This tool enables the modeling of semiconductor lasers and their arrays. Thermal calculations were based on the finite element method (FEM) applied to the steady-state heat conduction equation. A constant temperature of 300 K was assumed at the bottom surface of the heat sink, while adiabatic boundary conditions were imposed on all other surfaces. Electrical calculations were carried out by solving Laplace's equation coupled with the diode equation in a self-consistent manner. Detailed descriptions of the numerical models and material parameters are provided in references [5] and [6].

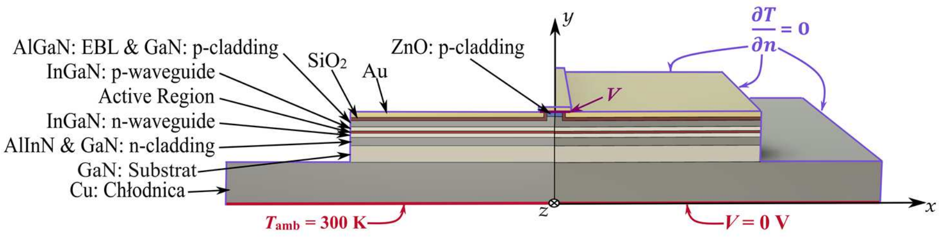

Fig. 1. Schematic of the nitride edge-emitting laser structure designed for green light emission at a wavelength of 540 nm [5]. The laser structure is based on a GaN substrate and incorporates n-type cladding layers composed of $Al_{0.83}In_{0.17}N$ and GaN, along with an n-type waveguide layer made of $In_{0.08}Ga_{0.92}N$. The active region consists of three $In_{0.29}Ga_{0.71}N$ quantum wells separated by GaN barriers. Above the active region, a p-$Al_{0.2}Ga_{0.8}N$ electron blocking layer is followed by a p-type waveguide ($In_{0.08}Ga_{0.92}N$) and a p-type cladding layer composed of p-GaN and ZnO. The top electrical contact is made of gold and is electrically insulated from the structure by a SiO_2 layer. A more detailed description of the device structure is provided in [6].

III. Results

Due to the geometry and boundary conditions of edge-emitting lasers, current and heat transport can be effectively analyzed using two-dimensional models. Self-consistent two-dimensional electro-thermal (2D TE) simulations for a single emitter, assuming a total heat dissipation of 1 W, resulted in a temperature rise of 37.9 K and required 11.5 minutes of computation time. A simplified two-dimensional purely thermal model (2D Ts), employing a concentrated heat source located in the active region, made the simulation 18 times faster but predicted a maximum temperature that was 16% higher.

Since real semiconductor lasers are inherently three-dimensional, 3D modeling provides a more accurate representation of heat dissipation within the structure, albeit at a significantly higher computational cost. The 3D electro-thermal (3D TE) simulations took approximately seven times longer than their 2D counterparts. The maximum temperature rise predicted by the 3D TE model was 9% lower, although the overall temperature distribution remained nearly unchanged. A simplified 3D thermal model (3D Ts), with heat sources confined to the active region, reduced the computation time by a factor of three but produced a 17% higher maximum temperature, while preserving the shape of the temperature distribution.

The discrepancies between the 2D and 3D models arise primarily from the inability of 2D models to account for heat spreading in the vertical (z) direction, which plays a critical role in thermal dissipation through the substrate, heatsink, and metal contacts. As a result, 2D models tend to overestimate the temperature rise compared to full 3D simulations.

To achieve a balance between accuracy and computational efficiency, a hybrid 3D Tr model was proposed, in which the spatial heat source distribution is imported from the 2D TE simulation. This approach reduced the computation time by a factor of 2.5 compared to the full 3D TE model, while preserving nearly identical temperature distributions, with a maximum deviation of less than 0.5%. Temperature distributions in the active region obtained from all considered models are presented in Fig. 2.

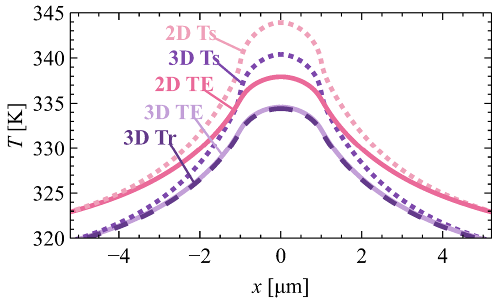

Fig. 2. Temperature distributions in the active region of a single emitter under 1 W of heat dissipation, as computed using various numerical models.

The comparison was further extended to a one-dimensional array consisting of ten edge-emitting nitride lasers. In this case, 3D models also resulted in significantly longer computation times—up to 18 times higher—while predicting average temperatures approximately 33% lower than those obtained from the 2D models. Simplified Ts models further overestimated peak temperatures, by 8% in the 2D case and 10% in the 3D case, relative to their respective TE counterparts. The hybrid 3D Tr model also demonstrated excellent agreement in the array simulations, with temperature deviations not exceeding 1% in any emitter. Temperature distributions in the active region obtained from all considered models are presented in Fig. 3.

All evaluated models exhibited very similar temperature differences between emitters (11–12 K), indicating that simplified models can be effectively employed for optimization tasks, such as designing arrays with uniform temperature profiles. This allows for a significant reduction in computation time while preserving qualitative accuracy.

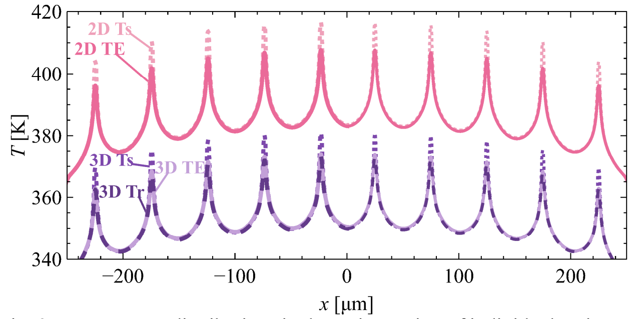

Fig. 3. Temperature distributions in the active region of individual emitters in the 10-element array, calculated for 1 W of dissipated heat per emitter, obtained using the analyzed computational models.

IV. Conclusions

This work presents a comparison of two-dimensional and three-dimensional thermal and electro-thermal numerical models used for the thermal analysis of nitride-based edge-emitting lasers and their one-dimensional arrays. The results demonstrate that 2D models can significantly reduce computation time, by up to a factor of 18 for arrays, while providing qualitatively accurate results. The average temperature overestimation compared to full 3D models is approximately 9% for a single emitter and 33% for arrays. However, the relative temperature distribution between emitters remains consistent across all models. A hybrid approach combining 2D and 3D simulations was also proposed, in which heat source distributions obtained from a 2D electro-thermal model are used in 3D thermal calculations. This method reduced computation time by a factor of 2 to 2.5 while maintaining high quantitative accuracy, with temperature deviations not exceeding 1%.

Acknowledgment

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