Impact of vertical structure on thermal lensing and lateral beam quality in high-power broad-area diode lasers

Mohamed Elattar, Juliane Rieprich and Paul Crump *(E-Mail: mohamed.elattar@fbh-berlin.de)*
Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany

Abstract: Proper regulation of the lateral thermal profile (lens) in broad-area diode-lasers (BALs) is essential for improved beam quality. New finite-element thermal-simulation-based analysis of measured thermal lenses in BALs is therefore presented. We show how the interaction of the thermal barrier resistance R_K at the semiconductor-to-metal interface with the vertical thermal conductivity profile of the epitaxial layers regulates the thermal lens. As R_K tends to 0, variation in the epitaxy has little impact on thermal lensing. For high (measured) R_k, the variation in epitaxy causes 1.4× variation in the lens curvature and comparable degradation in lateral beam quality of the BAL.

1. Introduction

In broad-area diode lasers (BALs), lateral beam quality is quantified using the beam parameter product BPP_{lat}, calculated as ¼ of the product of the near-field width and far-field angle. With increasing optical power, and the subsequent active-zone temperature increase ΔT_{AZ} due to non-zero thermal resistance R_{th}, BPP_{lat} has been shown to follow an empirical linear trend $BPP_{lat} = BPP_0 + S_{th}\cdot\Delta T_{AZ}$, as first proposed in [1]. The fit factors BPP_0 and S_{th} represent a non-thermal ground level and a thermal slope, respectively. Recently in [2], a long series of experimental results has been summarized, exploring a wide range of mechanisms that regulate BPP_0 and S_{th}, thus directly impacting BPP_{lat}. One of the primary mechanisms regulating S_{th} is thermal lensing, where refractive index locally increases with increasing temperature in the device center, thus establishing a strong lateral waveguide which allows the guiding of a large number of higher-order modes with high BPP_{lat} (i.e. low beam quality). It has been experimentally demonstrated that one of the factors regulating the strength of the thermal lens is the epitaxial layer structure used to construct the BALs [3,4]. In this work, we expand on the thermal simulation results presented in [2], based on finite element analysis using ANSYS, aiming to gain a deeper understanding of how the vertical structure impacts the thermal lens, subsequently affecting BPP_{lat}.

2. Review of experimental studies

In previous studies [3,4], thermal camera imaging of the front facet of a BAL under continuous-wave (CW) operation was used to obtain the lateral thermal profile within the plane of the active zone. As shown in Fig. 1(a), a quadratic fit function $T(x) = B_2\cdot x^2+B_1\cdot x+B_0$ was then applied to the thermal profile within ±60 µm of the center of the stripe, with the quadratic (bowing) term B_2 used as a measure of the strength of the thermal lens. These studies compared how B_2 and BPP_{lat} develop with increasing ΔT_{AZ} in BALs with different epitaxial layer structures, namely asymmetric super-large optical cavity (ASLOC) and extreme-double-asymmetric (EDAS) designs [3], with identical dimensions and p-side down mounting. Figure 1(c) demonstrates that although overall thermal resistance is very similar, S_{th} is roughly doubled using EDAS compared to ASLOC, and figure 1(b) shows a similar trend for the variation of B_2 with ΔT_{AZ}, which is about 40% higher using EDAS, indicating that the bowing variation rate $m_b = \Delta B_2/\Delta T_{AZ}$ is proportional to S_{th} and can therefore be used to estimate how different design changes would affect BPP_{lat}.

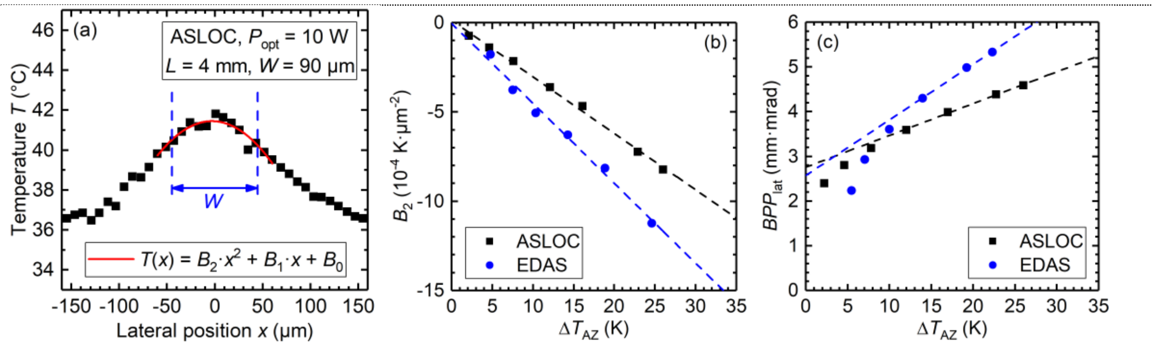

Figure 1: (a) Temperature as a function of lateral position, obtained from a thermal camera image of the front facet of an ASLOC BAL, mounted p-side down and operating at 10 W optical power (CW) and 25°C heat sink, with stripe and quadratic fit indicated. (b) Thermal lens bowing (quadratic fit term B_2) and (c) measured lateral beam parameter product as functions of change in active-zone temperature ΔT_{AZ} for two vertical structures ASLOC and EDAS (adapted from [2–4]).

3. Simulation model and results

As described in [5], the lateral thermal profile is simulated using ANSYS (finite element analysis tool), which is used to create a 2-D cross-sectional model of the BAL chip with all its epitaxial layers as well as the contact metallization, soldered p-side down onto the submount, with corresponding thermal conductivity values for each material, and a uniform longitudinal thermal profile assumed for simplicity. Heat generation within the chip is calculated at different operating points, and distributed appropriately depending on the amount of absorption, recombination, and Joule heat estimated from each layer. The lateral thermal profiles are vertically averaged over ±5 µm around the active zone, for better comparability with the thermal camera images with a limited resolution. It has been shown in previous work [5,6] that the p-side semiconductor-metal interface exhibits a large thermal boundary (Kapitza) resistance $R_K \approx 7\times10^{-6}$ m^2·K/W (inverse of thermal boundary conductance $h_K \approx 0.14$ MW/(m^2·K)), that increases the total thermal resistance and limits the transfer of heat out of the chip. We find that to reproduce measurement results in simulation, a thermal barrier (TB) layer with high R_{th} (~0.7 K/W) must be introduced between the p-side GaAs contact layer and the contact metallization.

ANSYS simulations are carried out for ASLOC and EDAS BALs at different operating points, with and without the TB layer in each case. Figure 2(a) shows that EDAS only exhibits significantly higher B_2 variation (~8.5%) with ΔT_{AZ} (i.e. higher m_b) when the TB layer is included, as needed to agree with the measurement results. Figure 2(b) shows that with increasing R_K at the interface (corresponds to increasing R_{th} of TB layer), the difference in m_b increases proportionally to the thermal resistance difference ΔR_{th} between the two structures. This indicates that the presence of the thermal barrier amplifies the thermal contrast between structures, thus increasing the impact of vertical design on R_{th}, S_{th} and BPP_{lat}. Figure 2(c) shows no significant change in m_b in case all the heat is generated inside the active zone, in comparison to the aforementioned realistic distribution of heat sources. This indicates that ΔR_{th} between ASLOC and EDAS is not due to a different spatial heat distribution, but rather due to the different thermal conductivity profiles of their epitaxial layer structures (c.f. [4]). These simulation results thus demonstrate that by altering the vertical structure and its thermal conductivity profile, the thermal lens could be weakened, thus reducing S_{th} and BPP_{lat}.

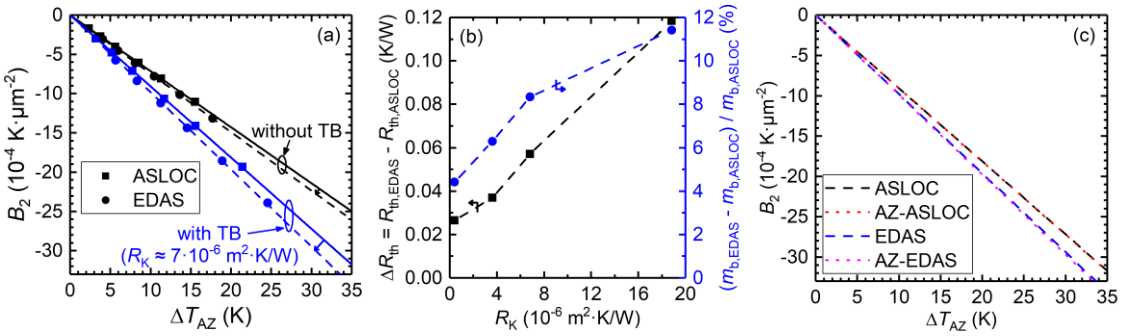

Figure 2: ANSYS simulation results for two vertical structures ASLOC and EDAS: (a) Thermal lens bowing (quadratic fit term B_2, c.f. Fig. 1) as a function of change in active-zone temperature ΔT_{AZ}, with and without a thermal barrier (TB) layer at the p-side semiconductor-metal interface. (b) Thermal resistance difference ΔR_{th} and relative difference in bowing variation rate (m_b) as functions of thermal boundary (Kapitza) resistance R_K (adapted from [2]). (c) B_2 as a function of ΔT_{AZ}, in case of a realistic distribution of heat sources along the vertical structure (ASLOC, EDAS) and in case of a single heat source, where all the heat is generated inside the active zone (AZ-ASLOC, AZ-EDAS).

4. Conclusion

We use thermal simulations based on finite element analysis to gain insight into the impact of vertical structure variation on thermal lensing and lateral beam quality in BALs, by comparing the variation of thermal lens bowing with increasing active-zone temperature in different epitaxial layer designs. In agreement with previous studies, we show that to reproduce experimental results in simulation, a thermal barrier layer should be included at the p-side semiconductor-metal interface. We then demonstrate that the difference in thermal lens bowing (correlates with beam quality) between vertical structures is proportional to the difference in their thermal resistance, which is a result of the interaction of the different thermal conductivity profiles of their layer structures with the thermal barrier.

5. References and acknowledgement

We thank TRUMPF Laser GmbH for supporting parts of this work.

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