Reducing of thermal resistance of edge-emitting lasers based on coupled waveguides

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Abstract. We present a study on minimization of thermal resistance of edge-emitting diode lasers by placing the active region closer to the laser surface. We demonstrate that using coupled large optical cavity (CLOC) approach one can reduce the thickness of the p-cladding down to 0.5 μm due to the strong mode localization in a broad active waveguide (1.35 μm) coupled to a passive optical cavity. Also, the advanced laser design allowed us to put the active region closer to the cladding in comparison with conventional broad waveguide lasers. As a result, a record-low thermal resistance of 2 K/W for 3 mm device directly mounted on a copper heatsink in combination with a low optical internal loss of 0.4 cm⁻¹ where demonstrated.

1. Introduction
Thermal resistance (Rth) of edge-emitting lasers plays a crucial role in its performance under high injection levels in a continuous wave (CW) regime. As the injection level grows, the active medium heats up and consequently diminishes the maximal output power. This effect is known as a thermal rollover [1]. Lower thermal resistance would provide better heat dissipation from the active medium resulting in higher CW optical power.

In diode lasers mounted epi-side down, a substantial fraction of the thermal resistance is associated with the layers located between the active medium and the epi-side surface covered usually with a thin metal film (metal p-contact). Hence, an evident approach for lowering Rth is to put the active region as close as possible to the epi-side surface. In conventional separate confinement heterostructures, intermediate layers between the active region and the surface have a typical total thickness of around 2 μm and include a highly doped cap layer, top cladding layer, and top part of a waveguide (WG) layer. Thinning of those layers requires a proper laser design, otherwise it may lead to p-metal diffusion, optical mode leakage, and increased fast-axis divergence angle, respectively. Longer laser cavities are favorable for effective heat dissipation since thermal resistance is inversely proportional to the cavity length [2]. However, this approach requires reducing the internal optical loss to compensate reduced mirror loss [3]. In this work, we present a study of InGaAs/GaAs/AlGaAs lasers with an advanced waveguide design intended for lowering both thermal resistance and internal loss.
2. Laser wafer design
Our waveguide design follows a novel concept of transverse mode engineering that is based on Coupled Large Optical Cavity (CLOC) approach allowing effective suppressing of high-order mode lasing [4]. Fundamental modes propagating in multimode waveguides would have better localization in the waveguide core resulting in a lower optical loss. Other advantages of such waveguides are the following: firstly, thick claddings are not required since the fundamental mode penetration into them is negligible; secondly, the active region can be easily shifted toward a cladding without fears of high-order mode lasing. Both things favor reducing the wafer thermal resistance. Following the basic idea, we have designed a laser structure (figure 1) comprising a GaAs active waveguide (thickness 1.35 μm) separated from 550 nm GaAs passive waveguide with 250 nm Al0.25Ga0.75As layer, and two p- and n-doped Al0.25Ga0.75As claddings. The active region based on two InGaAs quantum wells (wavelength about 1 μm) is strongly shifted toward the p-cladding which is as thin as 500 nm. As a result, the active region is located at the distance of only 920 nm from the epi-side surface. Transverse single-mode lasing is ensured by placing the active region in the minimum of the second mode and eliminating the first mode by using the CLOC technique.

![Figure 1. Scheme of the laser heterostructure: refractive index profiles (left axis) and simulated intensity profiles of the fundamental, second-order and two composite modes.](image)

3. Experiment details and results
The laser wafer was grown with metal-organic vapor phase epitaxy on an n-GaAs (100) substrate and processed into broad-area stripe lasers with 100-μm-wide uncoated apertures. Devices with various lengths were mounted onto a copper heat-sink with indium solder and tested both in pulsed and CW regimes. At all excitation levels, the lasers showed stable single-mode emission with the divergence of 33° FWHM (full width at half maximum) fully corresponding to the simulated one. As expected, the lasers showed a low internal optical loss of 0.4 cm⁻¹ being evaluated from the dependence of the reciprocal differential efficiency on the cavity length.

To calculated the thermal resistance $R_{th}$, we have made use of a modified technique based on the temperature dependence of the laser wavelength [5]. In the experiment, a thermal sensor providing a driving signal for a Peltier thermoelectric cooler (TEC) was placed at the heat sink 1.5 mm off the laser chip. Instead of commonly measured laser wavelength maximum, which in the case of broad-area multimode lasers may give an unrealistic value of $R_{th}$, we have investigated true spontaneous emission (TSE)
spectra collected with a 200 μm optical fiber through a top-contact window (figure 2a). A long-wavelength tail of the TSE spectrum follows the active region temperature (figure 2b). Meanwhile, the lasing peak demonstrates blue shift (reflecting the fact that the quasi-Fermi levels are not fully pinned at the threshold), which can be wrongly interpreted as the laser diode cooling.

![Figure 2](image)

**Figure 2.** Scheme of the laser mounting used for thermal resistance measurements (a). Increased dissipated power at the current of 4 A causes a blue shift of the lasing wavelength and red shift of the TSE wavelength (b).

Firstly, we have measured a temperature-induced red shift of the TSE wavelength of the 3 mm diode laser under pulsed excitation varying the heatsink and correspondingly the laser temperature (figure 3a). The calculated red shift of 0.37 nm/K is quite typical for GaAs/AlGaAs materials in a given wavelength range. Then, we have gauged the dependence of the TSE spectrum shift on the dissipated power (i.e. the input electrical power after deduction of the optical power) under CW pumping (figure 3b). It was found to be of 0.76 nm per 1 W. Taking these two values we have calculated the thermal resistance as low as 2 K/W, which corresponds to the specific thermal resistance as low as 6 K/W×mm. A characteristic temperature $T_0$ of the threshold current was found to be $\sim$110 K which is rather typical for lasers based on InGaAs/GaAs quantum wells.

![Figure 3](image)

**Figure 3.** Temperature-induced (a) and dissipated-power-induced (b) shifts of the TSE wavelength.

Both low thermal resistance and low optical loss allowed the lasers to exceed the optical power of 10 W under CW pumping.
4. Conclusion
In conclusion, we have demonstrated the possibility of reducing significantly the depth of the active region location in diode lasers intended for CW high-power operation. Taking advantage of the CLOC concept allow locating the quantum wells on the depth as shallow as 920 nm. As a result, 3 mm long devices demonstrate the thermal resistance of 2 K/W, which is, to the best of our knowledge, the lowest for diode lasers directly mounted on copper heat-sinks. Another advantage of the laser structure is extremely low internal optical loss (0.4 cm$^{-1}$), which allows us to use long-cavity diodes with the minimal impact on the slope efficiency.

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