Method for predicting junction temperature distribution in a high-power laser diode bar

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A hybrid experimental/numerical method is proposed for predicting the junction temperature distribution in a high-power laser diode (LD) bar with multiple emitters. A commercial water-cooled LD bar with multiple emitters is used to illustrate and validate the proposed method. A unique experimental setup is developed and implemented first to measure the average junction temperatures of the LD bar emitters. After measuring the heat dissipation of the LD bar, the effective heat transfer coefficient of the cooling system is determined inversely from the numerical simulation using the measured average junction temperature and the heat dissipation. The characterized heat dissipation and effective heat transfer coefficient are used to predict the junction temperature distribution over the LD bar numerically under high operating currents. The results are presented in conjunction with the wall-plug efficiency and the center wavelength shift.

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1. INTRODUCTION

High-power laser diodes (LDs) have emerged as the most promising pumping sources for solid-state lasers and fiber lasers, and they have been widely used in communication applications, cosmetic and medical applications, material surface treatment, joining technologies, cutting technologies, and defense applications [1–7]. The junction temperature is one of the most important parameters in achieving optimal performance of a high-power LD bar, determining the center wavelength, spectrum distribution, wall-plug efficiency, and reliability [8–12]. Thus, experimental and analytical determination of the junction temperature is critical for the proper operation of the diode as well as the development of the packaging design.

As higher optical power is demanded for advanced applications, more closely spaced emitters with higher forward current are used in LD bars. As a result, the junction temperature from the center to the edge emitters may have large variations, which makes the center wavelength and wall-plug efficiency of each emitter different from each other.

Several junction temperature measurement methods for low-power LDs or light-emitting diodes have been proposed, including techniques based on measurement of the thermal resistance [13], wavelength shift [14,15], optical power output [14], and forward voltage [14,16–23]. These methods are applicable only when the junction temperature is uniform. Micro-Raman spectroscopy [24–26] can be used to measure the junction temperature distribution by measuring multiple local temperatures. In practice, it requires a complicated experimental setup and has limited accuracy (10°C–20°C) [24–26].

The objective of this study is, thus, to propose a hybrid experimental/numerical method to predict the junction temperature distribution of a high-power LD bar. A commercial water-cooled LD bar with multiple emitters is investigated to illustrate the proposed method. After introducing the LD bar system, an experimental setup that is developed uniquely to measure the average junction temperatures of the LD bar is described. Two parameters critical to thermal analysis—heat dissipation and effective heat transfer coefficient—are determined and subsequently used to predict numerically the junction temperature distribution over the LD bar under high operating currents.

2. LASER DIODE SYSTEM

This section is devoted to the description and the electrical characteristics of a commercial water-cooled LD bar tested in the study.

A. LD Bar Description

The commercial LD bar system (E11.4N-940.10-150C-SO13.1: DILAS) is shown in Fig. 1(a). The LD bar consists of 23 identical GaAs emitters. The fill factor is 50%; each emitter is 200 μm wide and has a pitch of 400 μm. The maximum optical power at 160 A is 160 W with a center wavelength of 930 nm.

The close-up view of the side of the LD bar is shown in Fig. 1(b). The GaAs chip (the epi-down configuration) is...
mounted on a CuW submount using AuSn die attach. The submount made of CuW [coefficient of thermal expansion (CTE): 6.5 ppm/°C] is placed between the GaAs chip (CTE: 6.4 ppm/°C) and the water-cooled microchannel made of Cu (CTE: 16.6 ppm/°C) for the stress-relieving buffer layer to reduce the thermal stress attributed to the mismatch in the CTE between them as well as for the heat spreader [27–29].

The specified thermal resistance from the junction to water inlet temperature is approximately 0.3 K/W [30]. The internal structures of the commercial microchannel and the interfacial resistance are not available, and thus the effective water heat transfer coefficient for this commercial microcooler cannot be determined.

B. Calibration Curve

It has been known that a negative linear relationship exists between the junction temperature and the forward voltage of a laser diode [16–23]. The junction temperature at the operating current can be measured using this relationship (known as the “calibration curve”), and it is called the forward voltage method [16–23].

The “calibration curve” is obtained using a probe current much lower than the operating current. If the probe current is too low, the forward voltage loses the negative linear relationship at high junction temperatures due to the leakage current effect [31]. On the other hand, if it is too high, the loss of linearity occurs at low junction temperatures due to the internal series resistance [32]. In addition, the probe current should be as low as possible to avoid any undesired junction temperature increase while obtaining the calibration curve. Every LD has somewhat different electrical characteristics. Thus, it is important to determine the lowest probe current that provides the desired linearity [23].

The LD bar was placed inside a convection oven (EC1A: Sun Electronics Systems) and the forward voltage was measured at 25°C, 35°C, 45°C, 55°C, and 65°C (with an accuracy of ±0.1°C) by a data acquisition module (DAQ: USB-6212: National Instruments) with a 16-bit resolution. The maximum operating junction temperature was estimated, based on the thermal resistance of 0.3 K/W, the inlet water temperature of 20°C, and the measured maximum heat dissipation of 84.7 W (this will be explained further in Section 5.A), to be 45.4°C. The calibration curve measurement was repeated at various probe current values (from 20 to 160 mA with an interval of 20 mA).

The results are shown in Fig. 2, displaying the expected linear relationship between the forward voltage and junction temperature. The small deviations from linearity in voltage and temperature at 65°C are summarized in Table 1. The junction temperature error gradually decreased as the probe current

![Fig. 1. (a) LD bar with water-cooled microchannel [30] and (b) side view of the LD bar.](image-url)

![Fig. 2. Forward voltage as a function of junction temperature.](image-url)

<table>
<thead>
<tr>
<th>$I_f$ [mA]</th>
<th>Deviation of $V_f$ [mV]</th>
<th>Error in $T_j$ [°C]</th>
</tr>
</thead>
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<tr>
<td>20</td>
<td>1.60</td>
<td>1.3</td>
</tr>
<tr>
<td>40</td>
<td>0.80</td>
<td>0.7</td>
</tr>
<tr>
<td>60</td>
<td>0.80</td>
<td>0.7</td>
</tr>
<tr>
<td>80</td>
<td>0.78</td>
<td>0.6</td>
</tr>
<tr>
<td>100</td>
<td>0.41</td>
<td>0.3</td>
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<td>120</td>
<td>0.18</td>
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<tr>
<td>140</td>
<td>0.16</td>
<td>0.1</td>
</tr>
<tr>
<td>160</td>
<td>0.17</td>
<td>0.1</td>
</tr>
</tbody>
</table>
increased, and remained virtually the same after 120 mA. The probe current of 120 mA generated a heat dissipation of only 142 mW at 25°C (6.2 mW per emitter), which was negligible compared to the heat dissipation produced by the operating current. Thus, the calibration curve obtained at 120 mA was selected for junction temperature measurement. The slope and the y-intercept of the calibration curve were \(-1.21 \text{ mV/K}\) and 1.2104 V, respectively.

C. Electrical Resistance of Single Emitter

The calibration curve is obtained when all the emitters have the same temperature. The emitters of the LD bar are connected in parallel, and thus the electrical resistance of a single emitter (assuming that all emitters are identical) can be determined simply by

\[
R(T) = N \times \frac{V_f(T)}{I_{\text{probe}}}, \tag{1}
\]

where \(R\) is the electrical resistance of the single emitter \([\Omega]\); \(V_f\) is the forward voltage of the LD bar \([\text{V}]\) under the probe current, \(I_{\text{probe}}\) \([\text{A}]\); and \(N\) is the number of the emitter \((N = 23)\).

The results obtained for the LD bar at the probe current of \(I_{\text{probe}} = 120\ \text{mA}\) are shown in Fig. 3. The electrical resistance decreased with the temperature; the change in resistance was only 4% (from 226.2 to 216.9 Ω) over the temperature range from 25°C to 65°C.

3. JUNCTION TEMPERATURE MEASUREMENT

The junction temperature at the operating current can be measured by switching the operating current to the probe current [16–23]. As discussed in [33], the forward voltage shows the combined behavior of RC delay and thermal delay during the switching time. The RC delay is attributed to the resistance of a LD and the capacitance of a current source.

The LD bar is operated at very high forward currents. A power supply that drives high currents typically has large capacitance, which can cause the large RC delay, and the transient junction temperature behavior of the CuW submount cannot be documented. Fast switching circuits with two separate power supplies have been utilized to reduce the delay [19,20]. This scheme is adopted for the current study.

A. Test Setup

A test apparatus to minimize the RC delay is illustrated schematically in Fig. 4. The operating current source (LDX-36125-12: ILX Lightwave) applies the operating current with a nominal accuracy of ±(0.1% + 120 mA). The probe current source (2401: Keithley Instruments) applies the probe current with a nominal accuracy of ±(0.066% + 20 μA). The two power supplies are connected in parallel.

An N-channel metal–oxide–semiconductor field-effect transistor (MOSFET) (IRL7833PBF: International Rectifier Corporation) serves as a switch for the operating current source [19]. The probe current flows from the source (S) to the drain (D) of the N-channel MOSFET, even when the switch is off to block the operating current. A diode (150EBU02-ND: Vishay Intertechnology) is inserted between the operating current source and the MOSFET to prevent this undesired flow. The MOSFET and the diode are mounted on a heat sink to dissipate heat at high operating currents.

The chiller (ISOTEMP I 115 V/60 HZ PD-1: Fisher Scientific) regulates the water inlet temperature with a temperature stability of ±0.1°C, and the flow regulator (FLDW3211G: OMEGA Engineering) controls the flow rate. The optical power sensor (USB-PM-150-50: Coherent Laser Group) measures the optical power with a nominal accuracy of ±2.7% in the operating range. The current sources, the DAQs, and the optical power sensor are integrated into a LabVIEW program.

In the actual measurements, the chiller is set to produce the inlet water temperature of 20°C and the flow rate of 16 L/h. The pressure drop from the water-cooled microchannel cooler is 34 psi. The forward voltage measurement is conducted only with the probe current applied to the LD bar. As an example, to apply an operating current of 80 A to the LD bar, the operating current source and the probe current source applies 79.88 A and 120 mA, respectively, with the MOSFET switch “on.” When the optical power and the forward voltage of the LD reaches the steady-state condition, the switch is turned off to block the flow of the operating current. The data acquisition module 2 (DAQ2: USB-6212: National Instruments) supplies the gate voltage to the MOSFET switch and the data acquisition module 1 (DAQ1: USB-6212: National Instruments) measures the forward voltage of the LD with 16-bit resolution.
with the maximum sampling rate of 400 kS/s continuously during the transient period.

**B. Average Junction Temperature**

As mentioned earlier, the junction temperatures of emitters can have large variations at high operating currents. However, only a single value for the entire LD bar can be obtained from this setup. The following investigation is conducted to define the physical meaning of the measured value.

The emitters are connected in parallel, and thus the electrical resistance of the LD bar can be expressed as

$$R_{\text{bar}}(T) = \frac{1}{\sum_{i=1}^{N} 1/R_i(T_i)}$$

where $R_{\text{bar}}$ is the electrical resistance of the bar [Ω]; $R_i$ and $T_i$ are the electrical resistance [Ω] and the temperature of the $i$th emitter [°C], respectively.

Let us consider a case where the junction temperature of the LD bar increases linearly from the edge to the center ($\Delta T = T_{\text{center}} - T_{\text{edge}}$). This simple linear variation is analyzed to illustrate the physical meaning of the measured value. The average junction temperature of this case can be expressed as $T_{\text{ave}} = \frac{1}{N} \sum_{i=1}^{N} T_i$. Then, the true forward voltage and the forward voltage estimated based on the average temperature can be expressed as

$$V_{f}^{\text{true}}(T) = R_{\text{bar}}(T) \cdot I_{\text{prob}}; \quad V_{f}^{\text{ave}}(T) = \frac{1}{N} R(T_{\text{ave}}) \cdot I_{\text{prob}}$$

where $V_{f}^{\text{true}}$ is the true forward voltage of the LD bar [V]; $V_{f}^{\text{ave}}$ and $\frac{1}{N} R(T_{\text{ave}})$ are the forward voltage [V] and the electrical resistances [Ω] of the LD bar at the average junction temperature, respectively. It is to be noted that the true forward voltage and the forward voltage based on the average temperature are different because the emitters are connected in parallel.

The difference between these two values provides an estimate about how the true junction temperature deviates from the average junction temperature of the bar by dividing the slope of the calibration curve [V/K]. The deviation can be defined as

$$\delta T_j = \frac{V_{f}^{\text{true}} - V_{f}^{\text{ave}}}{1.21 \cdot 10^{-3}}$$

where $\delta T_j$ is the deviation of the true junction temperature from the average junction temperature of LD bar [°C]; $1.21 \cdot 10^{-3}$ is the slope of the calibration curve [V/K].

Figure 5 shows the deviation as a function of $\Delta T$. The deviation is less 1°C even for $\Delta T$ of 100°C. The small change in resistance with the temperature (Fig. 3) is attributed to this behavior. The results imply that the junction temperature determined from the forward voltage of the LD bar at the operating current can be considered as the average junction temperature of the LD bar in practice. This implication will be confirmed later with the actual nonlinear temperature distribution of the LD bar.

**C. Average Junction Temperature Measurement**

Figure 6 shows the transient voltage behavior of the LD bar obtained after blocking the operating current of 80 A. An extreme voltage peak at the beginning of the transient behavior is clearly visible. It was produced by an inductor voltage attributed to the large rate of current change (79.88 A to zero) and the nonzero inductance of the LD [34,35]. The peak was large but disappeared quickly after 200 μs.

Based on theoretical analysis [36–39], it is known that a junction temperature changes linearly in the square root of the time scale, if heat is dissipated in one direction through a homogenous material. In the case of this epi-down LD bar with the water-cooled microchannel cooler, the heat transfer through the GaAs substrate, and convection, as well as radiation, to the ambient surroundings is practically negligible (less than 1% of the total) due to the extremely large heat transfer coefficient in the water-cooled microchannel cooler (this will be discussed further in Section 4.B). Thus, the linear extrapolation in the square root time scale is applicable for the LD bar. The enlarged view of the region marked by a dashed box in Fig. 6 is
shown in Fig. 7(a). The voltage was converted into the temperature using the calibration curve (Fig. 2) and it was plotted in the square root time scale [Fig. 7(b)].

The transient junction temperature behavior can be divided into three zones. Zone 1 is the region dominated by the electrical delay. Zone 2 is the region where the linear junction temperature variation follows the square root time scale. When the propagating thermal wave reaches the microcooler interface, the transient junction temperature behavior of the CuW submount vanishes and we enter Zone 3. It is estimated from Fig. 7(b) that Zone 2 ends at $t = 1.57 \text{ ms} (= 1.25 \text{ ms}^{1/2})$. The following analytical analysis was conducted to confirm Zone 2.

The transient domain governed by the CuW submount can be calculated analytically using a time constant, which can be expressed as [40,41]

$$\tau_{th} = \frac{\rho c_p d^2}{k}.$$  \hspace{1cm} (5)

where $\tau_{th}$ is the thermal time constant [s]; $d$ is the thickness along the heat transfer direction [m]; $k$ is the thermal conductivity [W/m K]; $c_p$ is the specific heat [J/kg K]; and $\rho$ is the density [kg/m$^3$]. Material properties, thickness, and the calculated thermal time constant of CuW are listed in Table 2. A thermal time constant value for the CuW was determined as 1.37 ms, which is defined as the heating or cooling time required to produce a temperature change at the heat source (junction) equal to 63.2% of the total temperature difference between the initial and the final temperature. This value is reasonably close to the experimental observation, which confirms the validity of the experimental data.

The average junction temperature at the operating current was estimated from the linear extrapolation shown in Fig. 7(b); the estimated average junction temperature at 80 A was 35.6°C. The discrepancy in the repeatability of the average junction temperature measurement was less than 0.1°C, which was attributed to the probe current source inaccuracy.

The average junction temperatures were measured from 10 to 80 A at an interval of 10 A. The results are shown in Fig. 8. The connected lines between the measured data represent the trend of the results. As expected, the junction temperature increased with the current, but the rate started to decrease around the threshold current (26 A), where the stimulated emission began to occur; i.e., the higher wall-plug efficiency led to the reduction of the heat dissipation as well as the junction temperature. The heat dissipation as a function of the forward current will be discussed further in Section 4.A.

**Table 2. Material Properties, Thickness, and Calculated Time Constant Used in the Analytical Solution [28,29]**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density ($\text{kg/m}^3$)</th>
<th>Specific Heat ($\text{J/kg K}$)</th>
<th>Conductivity ($\text{W/m K}$)</th>
<th>Thickness ($\mu\text{m}$)</th>
<th>Time Constant (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuW</td>
<td>17300</td>
<td>160</td>
<td>200</td>
<td>300</td>
<td>1.37</td>
</tr>
</tbody>
</table>

Fig. 8. Average junction temperature at different forward currents.
4. HEAT DISSIPATION AND MICROCOOLER EFFECTIVE HEAT TRANSFER COEFFICIENT

The forward voltage and the emitted radiant flux are measured to quantify the amount of heat dissipation, using the following relationship [42]:

\[ P_h(T_j) = I_f(T_j) \cdot V_f(T_j) - \Phi(T_j), \]

where \( P_h \) is the heat dissipation [W]; \( I_f \) is the forward current [A]; \( V_f \) is the forward voltage [V]; and \( \Phi \) is the radiant flux [W]. After measuring the heat dissipation in Section 4.A, the effective heat transfer coefficient of the water-cooled micro-channel is calculated inversely from the numerical simulation, using the measured average junction temperature and the heat dissipation in Section 4.B.

A. Measurement of Heat Dissipation

The DAQ1 measured the forward voltage of the LD bar and the optical power sensor measured the optical power (the radiant flux) continuously. When the optical power and the forward voltage of the LD reached the steady-state condition, the values of forward voltage and optical power were recorded, from which the heat dissipation was calculated using Eq. (6).

The forward voltages, electrical input power (product of the forward voltage and the forward current), optical powers, and heat dissipations were measured as a function of current with an interval of 10 A. The results are shown in Fig. 9. The forward voltage and the electrical input power increased with the current. The optical power was virtually negligible before the threshold current (26 A) and increased linearly with the operating current after the threshold current. Similar to the junction temperature, the heat dissipation increased with the current and the rate started to decrease around the threshold current.

B. Effective Heat Transfer Coefficient

The numerical model (ANSYS 16.1) used in the current analysis is shown in Fig. 10. The model has the same geometry as the LD bar (23 emitters; emitter width of 200 μm and the fill factor of 50%, i.e., the pitch of 400 μm). A metallization layer (Ti/Pt/Au) between the emitter and the AuSn solder was not considered in the model due to the negligible thermal resistance. The values of thermal conductivity of GaAs, CuW submount, and AuSn solder used in the analysis are 54 W/m · K [43], 200 W/m · K [28,29], and 58 W/m · K [44], respectively.

The ambient temperature was set at 20°C (the same as the inlet water temperature). The effective heat transfer coefficient of the water-cooled microchannel cooler was assumed to be uniform on the bottom of the CuW submount. The effective heat transfer coefficients for natural convection (5 W/m² · K) and radiation (GaAs emissivity of 0.62 [45]) were set on the top and the sides of the model, albeit with the expectation of negligible effects on the junction temperature.

It is important to note that Eq. (6) is applicable only when the junction temperature is uniform. In addition, the uniform heat dissipation would be desired to determine the effective heat transfer coefficient most accurately. Thus, the lowest operating current (10 A) was used to calculate the effective heat transfer coefficient.

The heat dissipation obtained in Section 4.A was applied uniformly on the emitters, and then, the effective heat transfer coefficient was adjusted until the difference between the measured average junction temperature and the numerically calculated average junction temperature reached its minimum value. The average junction temperature difference, after typically five iterations, was less than 0.1°C, and the resulting effective heat transfer coefficient was found to equal 98 kW/m² K.

The junction temperature distribution at 20 A was also calculated to validate the effective heat dissipation. The difference coefficient was adjusted until the difference between the measured average junction temperature and the numerically calculated average junction temperature reached its minimum value. The average junction temperature difference, after typically five iterations, was less than 0.1°C, and the resulting effective heat transfer coefficient was found to equal 98 kW/m² K.

The junction temperature distribution at 20 A was also calculated to validate the effective heat dissipation. The difference coefficient was adjusted until the difference between the measured average junction temperature and the numerically calculated average junction temperature reached its minimum value. The average junction temperature difference, after typically five iterations, was less than 0.1°C, and the resulting effective heat transfer coefficient was found to equal 98 kW/m² K.
between the average junction temperatures (experimental and numerical) was less than 0.1°C, which confirmed the validity of the effective heat dissipation.

5. NUMERICAL PREDICTION OF JUNCTION TEMPERATURE DISTRIBUTION

It is important to understand the effect of the junction temperature on the heat dissipation before performing numerical analyses at high operating currents because Eq. (6) is applicable only when the junction temperature is uniform. The heat dissipation at 80 A was measured with three inlet water temperatures (10°C, 15°C, and 20°C). The junction temperature at each inlet temperature was also measured, and the results are summarized in Table 3.

As the average junction temperature increased from 25.6°C to 35.6°C, the forward voltage as well as the radiant flux decreased. The forward voltage reduction reduced the total electrical power consumption, while the radiant flux reduction increased the fraction of the input power converted to heat. It is worth noting that the net heat dissipation increased only by 2.2 W (or 4%) corresponding to the junction temperature increase of only 0.6°C, as the two parameters compensated their effects on heat dissipation [46]. The results indicate that the junction temperature dependency on the heat generation, over a range of 10°C, is not significant, which provides a technical rationale for the following numerical study.

A. Temperature Distribution in LD Bar

The heat dissipation and effective heat transfer coefficient obtained in the previous section were used to predict the junction temperature distribution over the LD bar numerically under high operating currents. The junction temperature distribution of the LD bar at 80 A is shown in Fig. 11(a). The GaAs substrate was not shown in order to clearly show the temperature distribution of the emitters.

The highest temperature occurred at the emitting side of the center emitter and the lowest temperature was observed at the opposite side of the edge emitter. The junction temperature decrease toward the edge emitter and the back end was attributed to the effect of the heat spreader. Because the edge emitter and the back end had cooling area enhancement from the CuW submount, more heat could be dissipated due to the extra heat spreading. The maximum temperature difference was 10.1°C. This result confirms that the application of uniform heat dissipation across all the emitters in a multiemitter LD bar can be expected to provide acceptable numerical results for input current of up to 80 A.

The junction temperature distribution was also calculated at the operating current of 160 A. Since the test apparatus was only capable of providing 125 A, an additional power supply (N5744A: Keysight Technologies) was connected to the operating current source in parallel to provide the additional current of 35 A. The forward voltage and the optical power at 160 A were 1.544 V and 162.4 W, respectively, and the heat dissipation was 84.7 W (65.7% wall-plug efficiency). It is to be noted that the average junction temperature could not be measured at 160 A because the threshold current of the MOSFET switch was around 90 A.

The junction temperature distribution of the LD bar at 160 A is shown in Fig. 11(b). The highest and lowest temperatures are 47.9°C and 31.7°C; the junction temperature difference is 16.2°C.

The average junction temperature of each emitter is compared in Fig. 12, where the only left half is shown due to the symmetry. The average junction temperatures remain virtually unchanged over the center half of the emitters (from #12 to #7) and then rapidly drop toward the edge emitter. The maximum average junction temperature differences among the 12 emitters are 4.9°C and 7.8°C at 80 A and 160 A, respectively.

The front-to-back junction temperature variations within the center (#12) and the edge (#1) emitter are plotted in Fig. 13. The junction temperature decreases exponentially from the emitting side to the back end. The junction temperature variations within the emitter are largest at the center emitter, and the magnitude increases as the operating current increases. The junction temperature variations of the center emitter are 5.4°C and 8.7°C for 80 A and 160 A, respectively.

The deviations of the true junction temperature from the average junction temperature of the bar were calculated with the actual nonlinear temperature distribution of the LD bar. Equation (3) was first used to determine the true forward voltage and the forward voltage from the average junction temperature: $V_{\text{true}}(80) = 1.168239$ V and $V_{\text{avg}}(80) = 1.168242$ V, and $V_{\text{true}}(160) = 1.157465$ V and $V_{\text{avg}}(160) = 1.157472$ V.

Table 3. Heat Dissipation at 80 A under Different Inlet Water Temperatures

<table>
<thead>
<tr>
<th>$T_{\text{inlet}}$ [°C]</th>
<th>10</th>
<th>15</th>
<th>20</th>
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<tr>
<td>$T_{\text{avg}}$ [°C]</td>
<td>25.6</td>
<td>29.2</td>
<td>35.6</td>
</tr>
<tr>
<td>$V_f$ [V]</td>
<td>1.458</td>
<td>1.457</td>
<td>1.456</td>
</tr>
<tr>
<td>$I_f \cdot V_f$ [W]</td>
<td>116.66</td>
<td>116.58</td>
<td>116.46</td>
</tr>
<tr>
<td>$\Phi$ [W]</td>
<td>67.80</td>
<td>66.85</td>
<td>65.34</td>
</tr>
<tr>
<td>$P_h$ [W]</td>
<td>48.9</td>
<td>49.7</td>
<td>51.1</td>
</tr>
</tbody>
</table>

Fig. 11. Temperature distribution of the LD bar at (a) 80 A and (b) 160 A.
The deviations were then calculated from Eq. (4); they were 0.002°C and 0.006°C for 80 A and 160 A, respectively. As expected from the small change in resistance with the temperature, the deviations were negligible. The results confirmed the validity of the proposed method.

**B. Wall-Plug Efficiency and Spectral Power Distribution**

The junction temperature change affects the wall-plug efficiency, which is defined as the optical output power divided by the electrical input power. Each emitter of the LD bar tested in the study produced an optical power of \(\approx 7.06 \text{ W}\) at the operating current of 6.95 A (the LD bar with 23 emitters at the operating current of 160 A).

It was reported in [47] that for a single emitter (a center wavelength of 975 nm) producing 6 W at 6 A, the wall-plug efficiency increased by 3% from 275 K (71%) to 260 K (74%). Thus, it is reasonable to assume that each emitter of the LD bar tested in the study has similar behavior to that of the single emitter reported in [47].

The power spectrum of the LD bar was obtained by a spectrometer (AvaSpec-ULS3648-USB2: Avantes) combined with a cosine corrector (CC-UV/VIS/NIR-5.0: Avantes). The diameter of the corrector was larger than the LD bar to ensure that the spectrometer received light from all 23 emitters equally. The output obtained from the measurement system was the irradiance (W/m²) of the LD bar as a function of wavelength. The power spectrum was obtained by normalizing the irradiance distribution by the peak irradiance. The results obtained at 30, 60, and 120 A are shown in Fig. 14.

LDs are known to show the spectral redshift (i.e., higher peak wavelength) at higher junction temperatures due to the reduced bandgap energy [48]. The spectral redshift caused by the junction temperature has been reported to be 0.28 nm/K [49] and 0.32 nm/K [50] for 808 nm and 980 nm LDs, respectively. The results in Fig. 14 show the redshift of \(\approx 0.3 \text{ nm/K}\), which is consistent with the reported values.

The results also show that the spectrum is broadened as the current increases; i.e., the larger full width at half-maximum at the higher forward current. The asymmetry of the spectrum (i.e., more broadening toward the lower wavelength) becomes more severe as the current increases. Both broadening and asymmetry are attributed to the larger junction temperature gradient at the high currents.

The analysis was based on a very large heat transfer coefficient. In practice, various thermal solutions can be employed for cooling the LD bar. In terms of the coefficient of performance (COP), the lower heat transfer coefficients (i.e., the decreased flow rate) can reduce the operating costs. However, the junction temperature will rise and the temperature variation within the LD bar will also increase with lower heat transfer coefficients. This will increase the asymmetry of the spectral power distribution (SPD) and the peak wavelength shift, which can reduce the pumping efficiency [6].

A high heat transfer coefficient is desired to increase the pumping efficiency, which can be achieved with an extreme flow rate of a coolant. However, the higher flow rate reduces

![Fig. 12. Average junction temperature of each emitter in the left half (symmetry).](image1)

![Fig. 13. Junction temperature variations along the emitter.](image2)

![Fig. 14. Normalized power spectrum at 30, 60, and 160 A.](image3)
the COP, which increases the operating cost. In addition, it can accelerate the erosion process of the surface structures inside microchannels, which will increase the junction temperature and will eventually reduce the lifetime of the LD bar [51,52]. Consequently, optimization of thermal solutions for high-power LD bars should be sought while considering the operating cost as well as various thermal, mechanical, and optical aspects of the system.

6. CONCLUSIONS

A hybrid experimental and numerical method was proposed and implemented for predicting the junction temperature distribution of a high-power LD bar. A commercial water-cooled LD bar was utilized to illustrate and validate the proposed method. The average junction temperature and the heat dissipation were measured, and the effective heat transfer coefficient of the cooling system was determined inversely using numerical simulation. The characterized properties were used to predict the junction temperature distributions of the LD bar at the extreme operating currents. The results showed significant junction temperature variations not only among emitters (7.8°C) but also along each emitter (8.7°C) at 160 A, which increased the asymmetry of the power spectrum. In addition, the expected redshift and the spectral broadening were observed. The proposed method can be used to determine the proper operation condition of the LD bar as well as to evaluate designs during packaging platform development. The future work will address a methodology to define the optimum design of LD bars considering the COP, performance, and reliability.


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