academicJournals

Vol. 8(10), pp. 362-370, 16 March, 2013
DOI: 10.5897/IJPS12.615
ISSN 1992-1950 © 2013 Academic Journals
http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Full Length Research Paper

Temperature dependence of wall-plug efficiency of high power laser diodes

Muzahim I. Azawe

Department of Physics, College of Education, University of Mosul, Mosul, Iraq.

Accepted 6 March, 2013

Temperature dependence of wall-plug efficiency of high power laser diodes is theoretically analyzed in terms of experimentally measured parameters of the device. This issue has an influence on the available power output and on the degradation mechanism. High power laser diodes have become increasingly important as the output power of such devices continues to rise. The present calculations revealed that the decrease of wall-plug efficiency with temperature could be explained, presumably in terms of excess voltage loss and internal waveguide optical loss. Understanding the dynamic mechanism of the decrease of efficiency can lead to optimum operating conditions of the device. Thermally rolling power runaway is found to be an important factor in the high power laser diodes degradation and eventually to device failure

Key words: Laser diodes, high power, wall-plug efficiency, internal loss, waveguide loss.

INTRODUCTION

High power laser diodes are appropriate light sources for enormous applications due to their high power conversion efficiency. The primary issue limiting the maximum power of these devices is self-heating (thermal rolling) at high drive currents (Li et al., 2007). For low-series-resistance and thermal-resistance device, it is found that the junction-temperature rise in CW operation is a strong function of both the characteristic temperature for external differential efficiency as well as of the heatsink thermal resistance (Botez, 1999) thermal resistance effect will be shown in this article.

Thermally affected high power laser (HPL) parameters will be studied in this work. Based on our experimental results, the temperature dependence of the crucial parameters of high power laser diodes will be investigated numerically. Among these are; the slope efficiency, wall-plug efficiency, and the internal loss. These critical device parameters, in addition to the hetero-barrier leakage and series resistance have to be optimized to yield maximum light powers (Schmidt et al., 2005). Thermal resistance will be shown in this article to be increased with optical power output, which degrades the efficiency of the device. Recently, it has been showed that low thermal resistance can provide high slope efficiency by the lithographic approach (Demir et al., 2010). Thermal properties of laser diode chips can be described by a thermal time constant associated with the heat spreading volume in the substrate (Shan et al., 2010). The efficient heat extraction from the substrate by excellent cooling system will be the most crucial issue for high power conversion efficiency. The temperature dependence has to be taken into account in any laser design for high power conversion efficiency.

Theory

The wall-plug efficiency of a high power laser diode is given by:

*Corresponding author. E-mail: Muzahim_935@yahoo.com. Tel: 07703630865.

$$\eta_C = \frac{P_{opt}}{P_{elect}} \tag{1}$$

where P_{opt} is the optical power output, P_{elect} is the electrical input power. The dependence of P_{opt} on the pumping current above threshold can be described as (Diehl et al., 2006):

$$P_{opt} = \eta_{slope}.(I_{op} - I_{th}) \tag{2}$$

with η_{slope} is the slope efficiency. The slope efficiency is related to the external differential quantum efficiency η_{ext} as (Behringer, 2007):

$$\eta_{slope} = \eta_{ext}.\frac{\hbar\omega}{q} \tag{3}$$

$\frac{\hbar\omega}{q}$ is the necessary voltage needed to get the required injection current, I_{op} is the operating current, and I_{th} is the threshold current. The electrical input power can be written as:

$$P_{elect} = V_{op}.I_{op} + R_s.I_{op}^2 \tag{4}$$

with V_{op} is the applied voltage at the operating current, and R_s is the series resistance. In this paper, the applied voltage will depend on the input power. The dissipated power in the laser is:

$$P_{dis} = I_{th}.\eta_{ext}.\frac{\hbar\omega}{q} + I_{op}(V_{op} - \eta_{ext}.\frac{\hbar\omega}{q}) + R_s I_{op}^2 \tag{5}$$

The temperature rise of the active region is connected to the dissipated power through the thermal resistance, R_{th} as (Laikhtman et al., 2005):

$$\Delta T = R_{th}.P_{dis} \tag{6}$$

The temperature dependence of threshold current and slope efficiency can be described as exponential functions with two specific constants T_o and T_l as (Bai et al., 2010; Botez et al., 1996):

$$I_{th}(T_{j2}) = I_{th}(T_{j1})\exp(\frac{T_{j2} - T_{j1}}{T_o}) \tag{7}$$

$$\eta_{slope}(T_{j2}) = \eta_{slope}(T_{j2})\exp(\frac{T_{j1} - T_{j2}}{T_l}) \tag{8}$$

Here, I_{th} and η_{slope} are measured at the different junction temperatures T_{j1} and T_{j2}. It is very difficult to get values for T_o and T_l from principles, but relatively simple to extract them from measurements. Higher barriers and lower threshold current will increase the values of T_o and T_l giving laser with better temperature stability.

Device parameters

Non-coated anti-reflection (AR) bar laser diodes (BLD's) with reduced linewidth, increased spatial brightness, and low thermal resistance was used in the experiments. Low thermal resistance was achieved in our setup by minimizing the intra-package and package to heat sink interface which will enable the device to work with high power and external efficiency. On the other hand, low thermal resistance enable the BLD to be operated CW without sacrificing operating lifetime in addition to the superior performance.

Depending on the thermal resistance, the heat dissipation in laser diodes results in an active region temperature rise. This temperature rise limits the output power (through so-called thermal rollover) and enhances the device degradation mechanisms. It is therefore critical to minimize the thermal resistance in high-power laser devices.

Narrow linewidth and stable wavelength emission were maintained during the operation by the influence of high accurate current driving circuitry and temperature controller. The mount of the BLD had the ability to control the temperature of the active region within the required stability with both the thermo-electric cooler (TEC) and the liquid nitrogen (the cryostat). A slope efficiency η_{slope} of (1.3024 W/A), threshold current I_{th} of (6.2 A), series resistance R_s (7.6 mΩ), thermal resistance R_{th} (1.2 K/W), and wavelength (803.08 nm) at a temperature (19°C) were the device parameters found experimentally. Other parameters, which can be affected by temperature, were also obtained for the sake of numerical simulation, $\partial\lambda/\partial T = 0.43 nm/^{o}C$ and $\partial V_{be}/\partial T = -2.7 mV/^{o}C$. The characteristic temperature coefficient of threshold current density was extracted from the measurements, as differ for every type of laser diode (T_o = 113°C).

The maximum power conversion efficiency (PCF) is expressed as (Ma and Zhong, 2007; Kanskar et al., 2003):

$$\eta_{PCF_{max}} \cong \eta_{ext}.\frac{V_F}{V_{be}}(1 - 2\sqrt{R_s I_{th}/V_{be}}) \tag{9}$$

where V_F is the quasi-Fermi level difference, and V_{be} is the overall built- in voltage. In order to calculate the slope efficiency of the device, light power output versus current at different temperatures were recorded. The slope of $\left(dP/dI\right)_T$ above threshold (stimulated emission), converted to the external differential quantum efficiency η_{ext}, was calculated and drawn at each temperature. The dependence of η_{ext} on the temperature from this plot, for the device under test, was found to be of the form:

$$\eta_{ext}(T) = (1.77_{T=16^{o}C})\exp\left[-.(\frac{T-16}{24.63})^2\right] \tag{10}$$

Provided that T is in °C. This formula is numerically obtained for the experimental variation of the external differential quantum efficiency with temperature with curve fitting tool in Matlab provided that R-square of the fitting is nearly equal one. This equation differs slightly with the equation given by (Suchalkin et al., 2002).

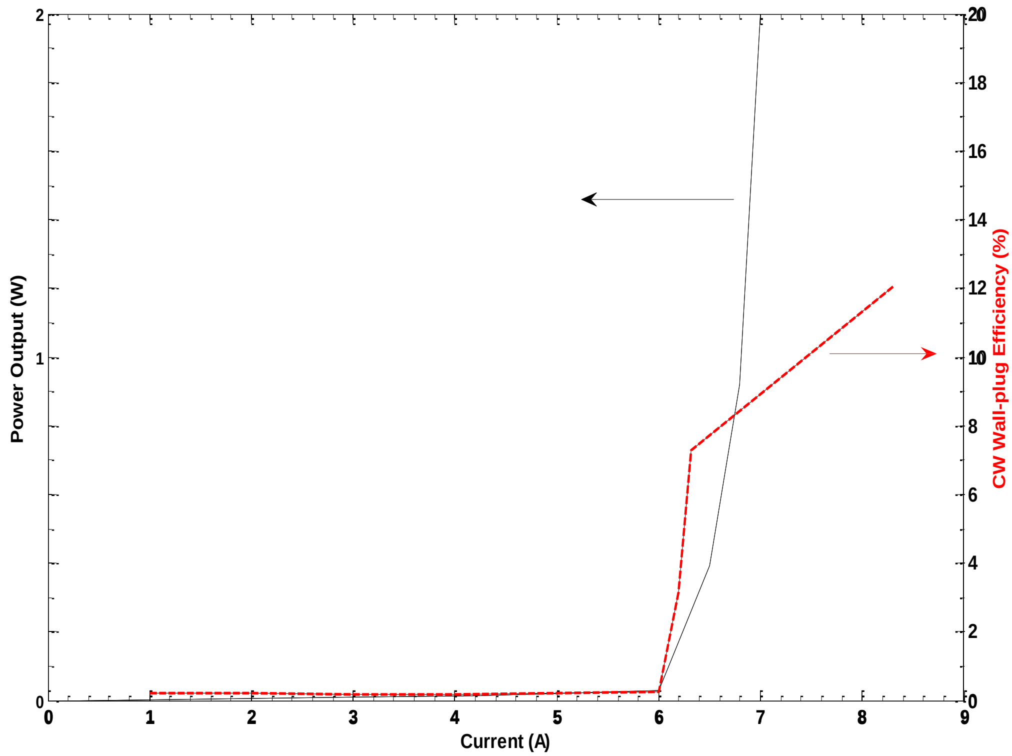

Figure 1. CW power output and wall-plug efficiency at a controlled temperature of 16°C.

Power conversion efficiency is temperature dependent through the dependence of all parameters given in Equation (9) on temperature, in other words, η_{PCF} is temperature dependent as will be shown later.

The next step is to find the modal gain from the threshold condition which can be stated as:

$$R.\exp\{(\Gamma G-\alpha_{tot})L\}=1 \quad (11)$$

where *R* is the facet power reflectivity, Γ the confinement factor, G the material gain, α_{tot} is the total loss, and L is the laser cavity length. The material gain *G* is sufficiently small when the total loss α_{tot} is to be estimated from the low energy side of the modal gain spectra (Suchalkin et al., 2002), that is:

$$g=\Gamma G-\alpha_{tot} \quad (12)$$

$$g\approx-\alpha_{tot} \quad (13)$$

Subtracting the mirror loss α_m, $\left\{\alpha_m=\left(\frac{1}{L}\right)\ln(R)\right\}$ from the total loss gives the internal loss. The temperature increase of α_{tot} is the issue of this work. The coefficient of gain saturation had been neglected in the calculations, since it has a minor effect on the high power output of the device.

RESULTS AND DISCUSSION

In order to get a full understanding of the HPL characteristics, the power and wall-plug efficiency versus the input current are shown in Figure 1, provided that the temperature was controlled at 16°C. This experimental plot was recorded while maintaining the driving in control circuit with accuracy around ±0.1A. The power was obtained just over 2W without any kink or thermal runaway to ensure linear operation and without mode hopping. At this power level, wall-plug efficiency can be estimated with good accuracy.

Wall-plug efficiency increases with the input current and reaches its maximum value at a current value of (8A). This available power output and high efficiency were all due the coolant instrument applied to the HPL mount.

The parameters that have an impact on the power conversion efficiency (Equation (2) is V_{be}, and the quasi-Fermi separation V_F (it can be determined from the lasing wavelength), in addition to their dependence on temperature, they are affected by the input power as shown in Figure 2. The wavelength had been recorded with a high stability in driving current and temperature. The wavelength was recorded by the monochromator with a wavelength step of 0.1 nm. The assumption of that the quasi-Fermi separation V_F to be consistent with the

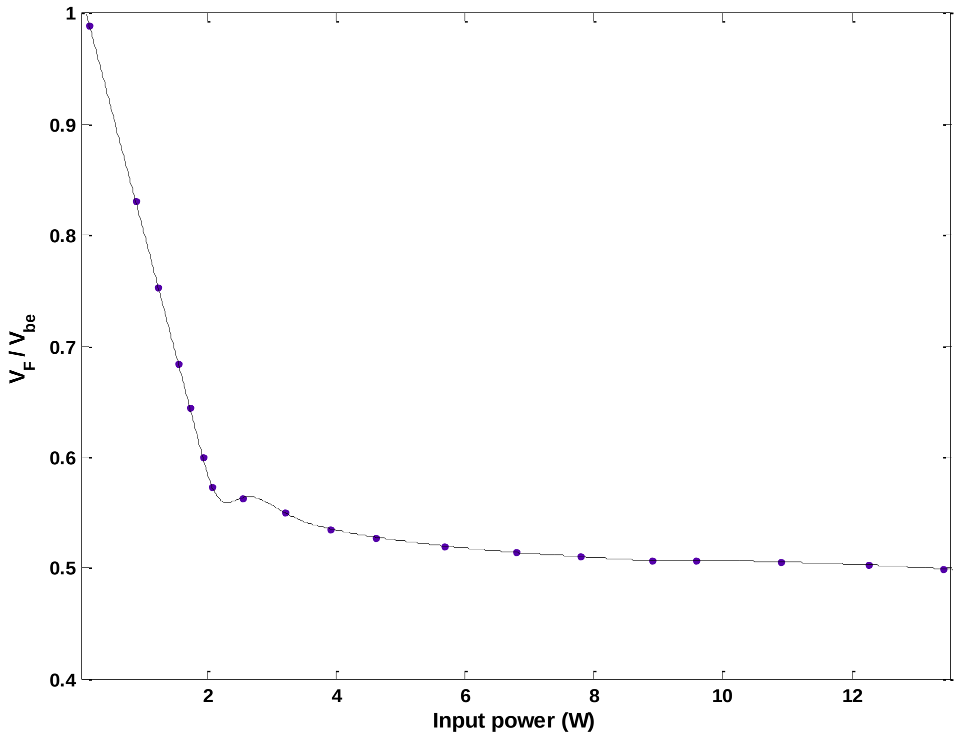

Figure 2. The ratio of quasi-Fermi level difference to the overall built- in voltage as a function of input power of HPL.

clamping of the carrier density to its threshold value when the stimulated emission was reached (gain = losses). The usual measurements are to record the spectra of laser diode above threshold and driving with the laser diode with pulses of low duty cycle to reduce the heating effect. Mechanical chopper is used to chop the laser beam. The detector was integrated with preamplifier and lock-in amplifier with reference frequency from the chopper.

As can be seen from the plot that, the quasi-Fermi separation and the built-in potential equals each other before applying any current to the HPL device, and the ratio decreases rapidly and reaches its maximum decrease after threshold current had been reached. Figure 3 shows the influence of temperature on the power dissipation in the laser given by the Equation 4.

The evaluation of power dissipation in the laser was calculated by taking into account the dependence of the terms given in Equation 4 on the temperature, especially threshold current, slope efficiency, and series resistance, as stated in the above. As can be seem from the graph, the power dissipation is high at elevated temperature.

The wall-plug efficiency, as stated above, is mainly dependent on the internal loss mechanism of the high power laser diode. The input power that is not converted to light output power is considered as wasted power (heat). This heat has to be removed from the laser mount, otherwise, more power must be added to overcome the losses, and hence the junction temperature will rise and ultimately shorten lifetime of the laser diode (Williamson and Kanskar, 2004).

The temperature rise in the active region of the HPL when the temperature control was stabilized only by the TEC is found to be very high as given in the following Figure 4. This temperature rise was calculated from power dissipation and thermal resistance as a function of temperature at different operating currents, Equations 4 to 7, and taking into account Fourier's law of heat conduction for the heat sink temperature calculations. This rise can be very crucial on the lifetime and power conversion efficiency of the HPL and hence on the wall-plug efficiency. The figure also illustrates the need for more efficient temperature control, for example cascaded TEC, good thermal interface materials.

The variation of thermal resistance with optical power output is shown in Figure 5. Light output above threshold is expressed as in Equation 2 and it is temperature dependent and a self-consistent numerical simulation was applied to obtain the two characteristics T_o and T_l. The thermal resistance values for our device which was cooled actively were found and plotted as a function of power output, taking into account the variation of slope efficiency and threshold current with temperature. The line was drawn as a theoretical fit for the experimental

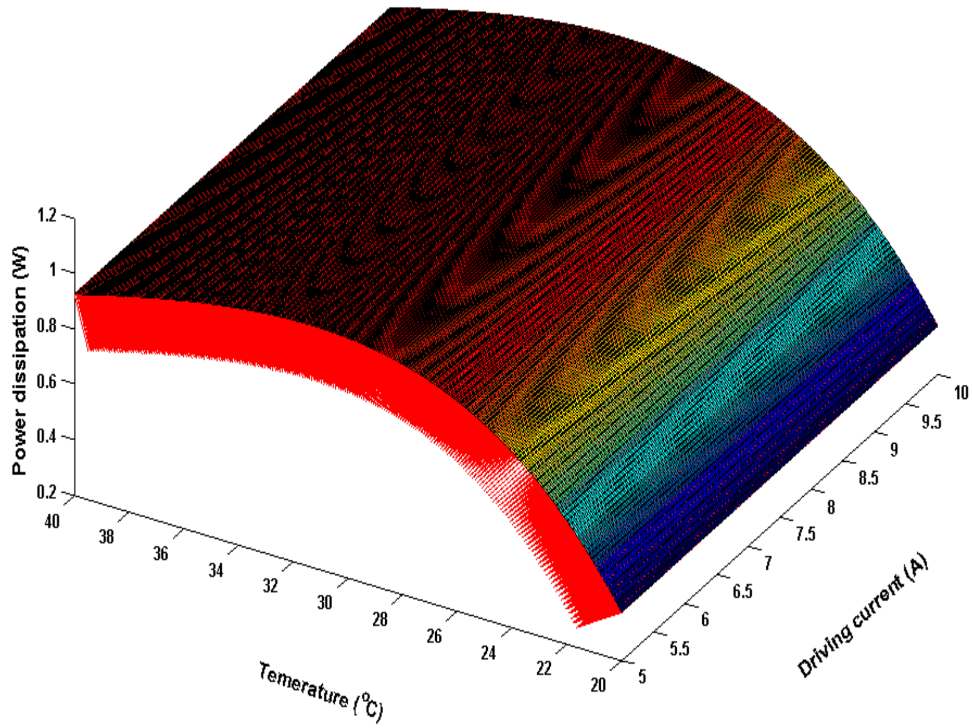

Figure 3. The power dissipation dependence on both the driving current and the temperature of the heat sink.

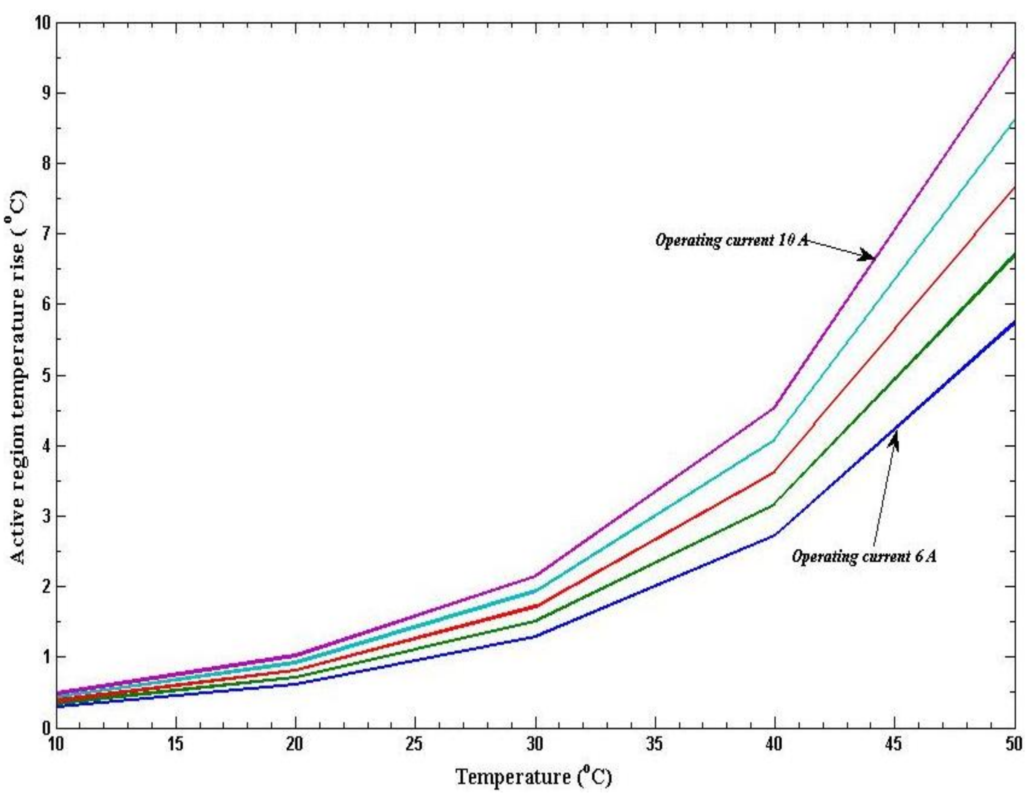

Figure 4. Temperature rise of the HPL active region as a function of heat sink temperature control with TEC at different operating currents.

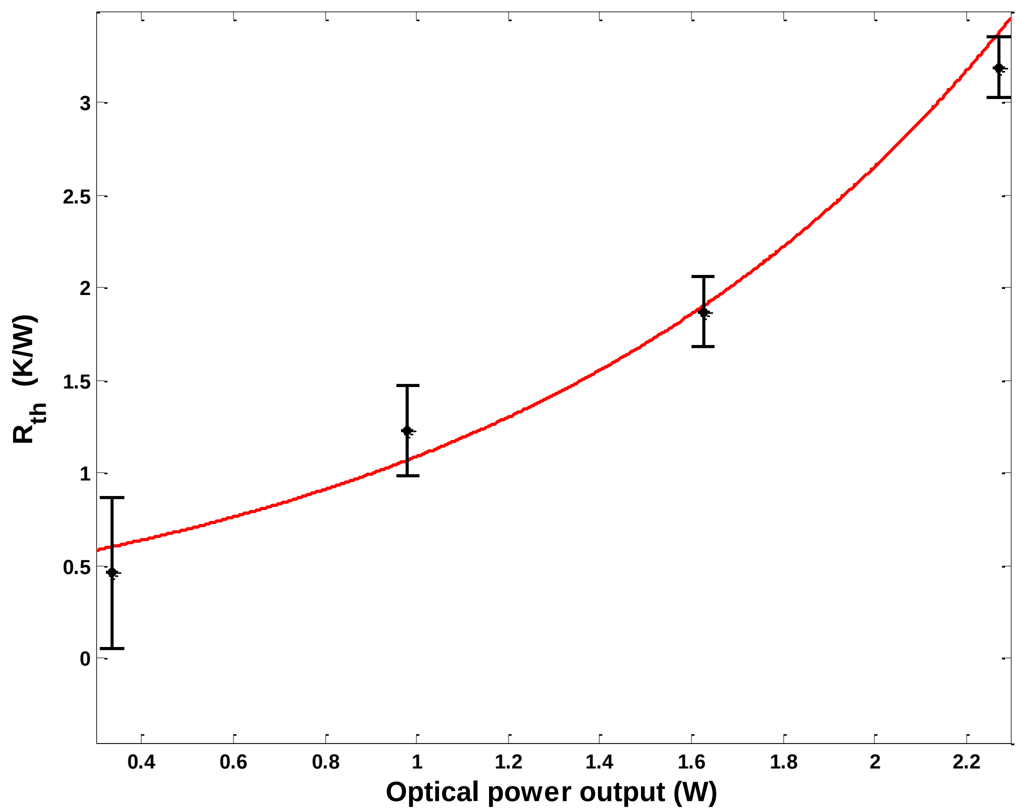

Figure 5. Thermal resistance of the HPL with optical power output. Solid line represents the theoretical simulation.

data. Thermal resistance high increase will have an impact on the wall-plug efficiency of the device, as will be shown.

The band gap energy of the semiconductor lasers variation with temperature follows the Varshni relation (Sze, 1985), which indicates quadratic temperature dependence, and this dependence has to be included in our calculations as well. The other effect that has to be included is the wavelength-shift with temperature.

To study the power conversion efficiency of the HPL as a function of temperature, Equation 8, we have to consider the terms given by this equation as temperature variables, that is, threshold current, external differential quantum efficiency, overall built- in voltage, and series resistance. Figure 6 shows the power conversion efficiency as a function of temperature. The plot shows that overall built- in voltage, series resistance and external differential quantum efficiency are the most effective parameters on this efficiency when they are considered to be as temperature dependent or not. The efficiency drops out to 50% when these parameters were taken as temperature dependence, provided that the BLD was stabilized efficiently to overcome the active temperature rise.

The reliable operation of HPL with improvement power conversion efficiency requires high T_o and T_l, in order to suppress the dependence on the temperature of the series resistance, built-in voltage, and external differential quantum efficiency. In addition, the decrease of series resistance leads the increase in the electrical-to-optical conversion. The influence of series resistance has to be considered in any design of the HPL.

Now, the effect of temperature on the characteristics of the HPL especially that can influence the wall-plug efficiency variation with temperature will be studied thoroughly. The slope efficiency in conjunction with η_{ext}, and the internal loss had to be evaluated with temperature variations in order that the wall-plug efficiency and its variation with temperature need to be asserted. The slope efficiency as a function of temperature is shown in Figure 7.

The decrease of η_{slope} with the temperature is due to the increase of internal loss, loss of carriers over the heterobarriers, and nonradiative recombination (C.F. Equations 4 and 5). The thermal carrier loss mechanism can be combined with gain measurement and calculation (Jian and Summers, 2010).

As stated above that the internal loss increases with temperature due to many mechanism influenced by the

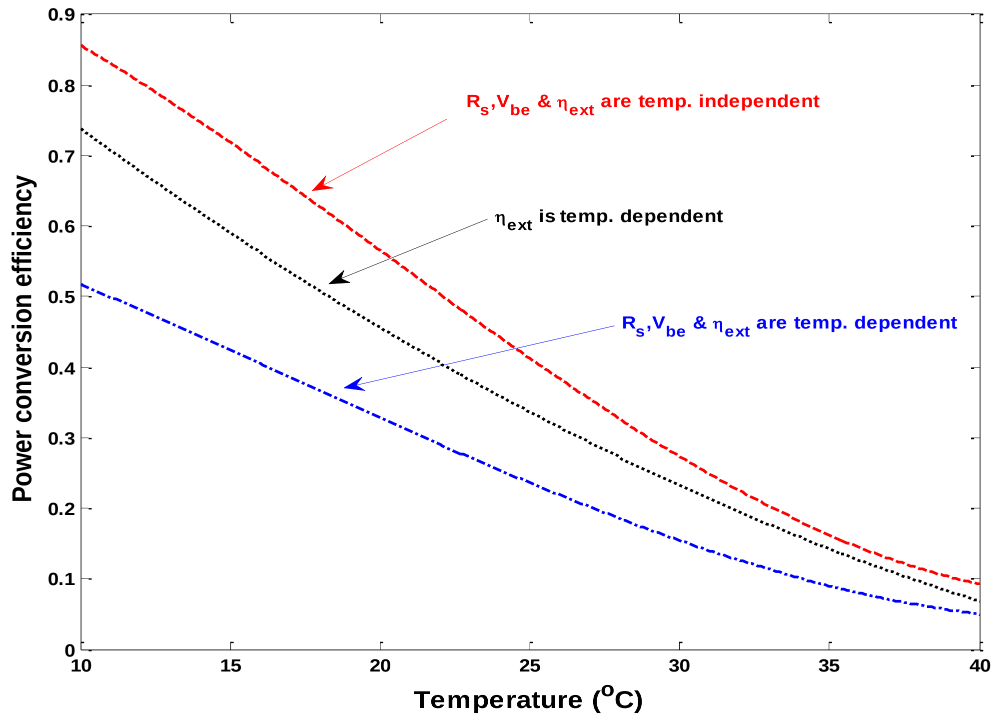

Figure 6. Illustrates the influence of R_s, V_{be}, and η_{ext} on the power conversion efficiency as a function of temperature.

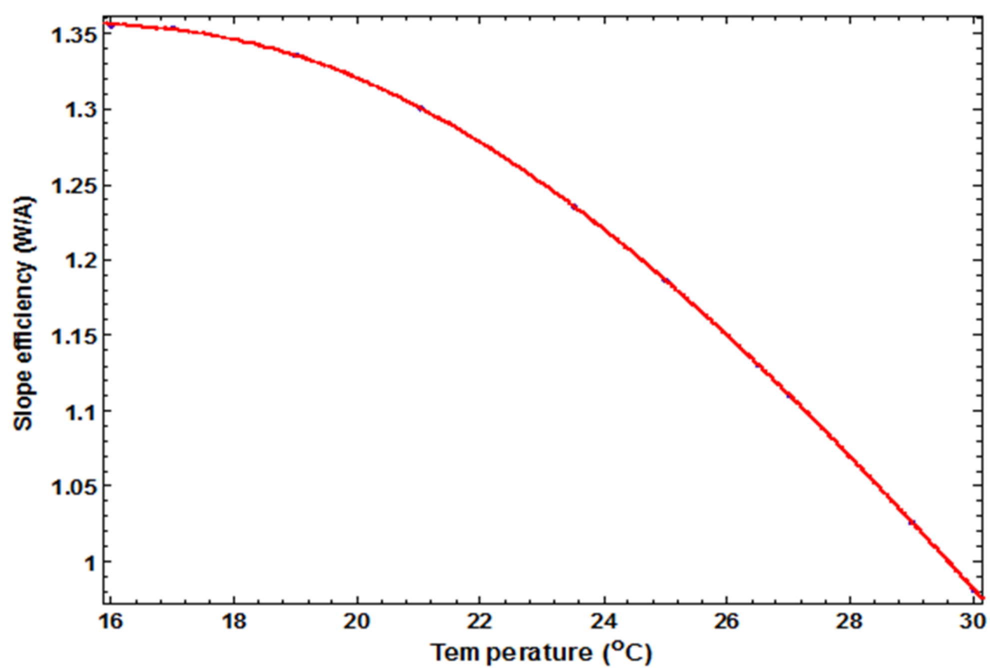

Figure 7. Slope efficiency of HPL variation with temperature.

temperature rise and their effects became pronounced. The internal loss increment with temperature is illustrated in Figure 8. Low internal loss increases external quantum efficiency, it is the low series resistance R_s , and hence,

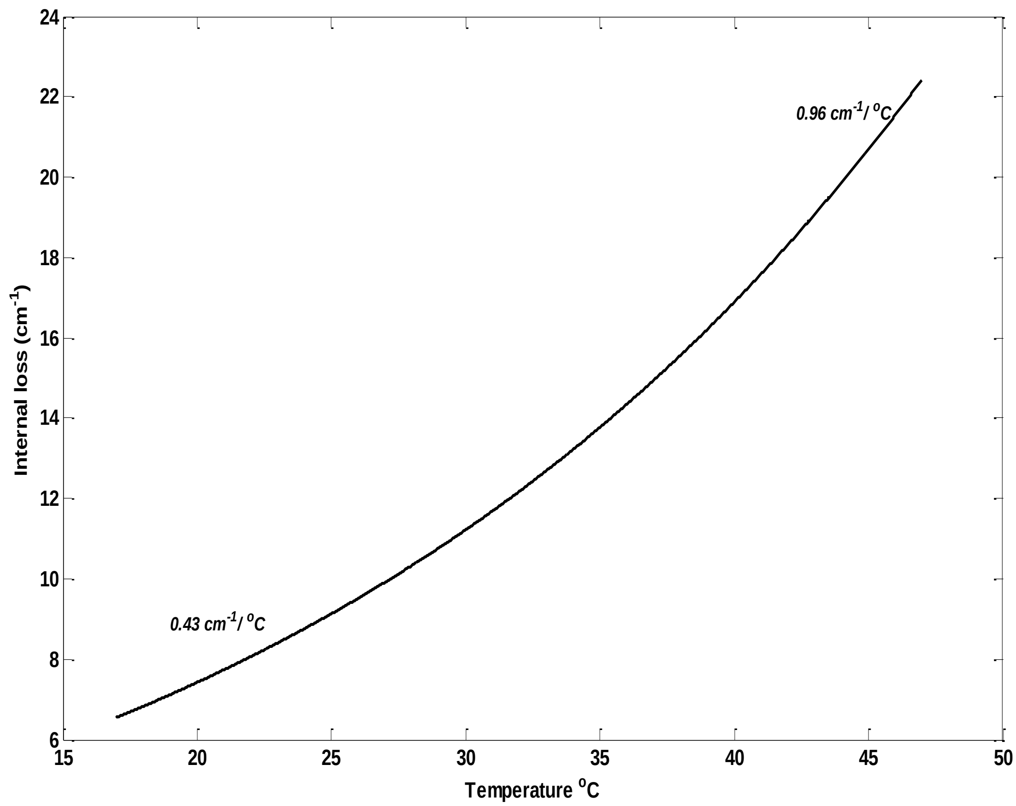

Figure 8. Dependence of internal loss on the temperature of the HPL.

the low forward voltage of these devices, that enables the relatively high CW output powers (Equation 1).

The important parameter of the HPL is the wall-plug efficiency, and hence its dependence on the operating temperature. Wall-plug efficiency calculation had been found to decrease with temperature, as can be seen from Figure 9. This efficiency of the high power laser diodes is a collection of over-all efficiency of the device and gives the exact picture of the characteristics parameters. The efficiency η_{PCF} can be written as:

$$\eta_{PCF} = \eta_1 . \eta_2 . \eta_3 . \eta_4 \qquad (13)$$

where η_1 accounts for laser diode efficiency, η_2 for the excess voltage ratio, η_3 accounts for pumping carrier loss, and η_4 for total loss (internal loss + mirror loss). The impact of temperature on the wall-plug efficiency can be interpreted by many factors, carrier leakage and nonradiative recombination for lowering the value of η_1. The second stands for the excess voltage loss. The third term accounts the material quality (series resistance, structure). The last term is the internal waveguide optical loss.

To focus on η_{PCF} to be dependent on the HPL device parameters, we can draw the following assumptions because, all the efficiency terms are interrelated; the laser diode efficiency η_1 =1, the η_{PCF} can be further elaborated as:

$$\eta_{PCF} = \frac{V_{op}.I_{op} + R_s.I_{op}^2}{I_{th}.\eta_{ext}.\frac{\hbar\omega}{q} + I_{op}(V_{op} - \eta_{ext}.\frac{\hbar\omega}{q}) + R_s I_{op}^2} x \frac{\ln\left(\frac{1}{R}\right)}{2\alpha_{\text{int}} L + \ln\left(\frac{1}{R}\right)} \qquad (14)$$

The maximum obtainable wall-plug efficiency is formulated as in Equation 9. The maximum value of η_{PCF} is mainly dependent on the operating current and the parasitic device parameters. The series resistance can be decreased by increasing the length of the cavity and in turn lowering the threshold gain. It also implies the reduction in the forward operating voltage for higher electrical power efficiency. The conventional approach to determine the current injection efficiency is in the above threshold regime, using a cavity length analysis (Coldren and Corzine, 1995).

Conclusions

The wall-plug efficiency (WPE) of HPL had been

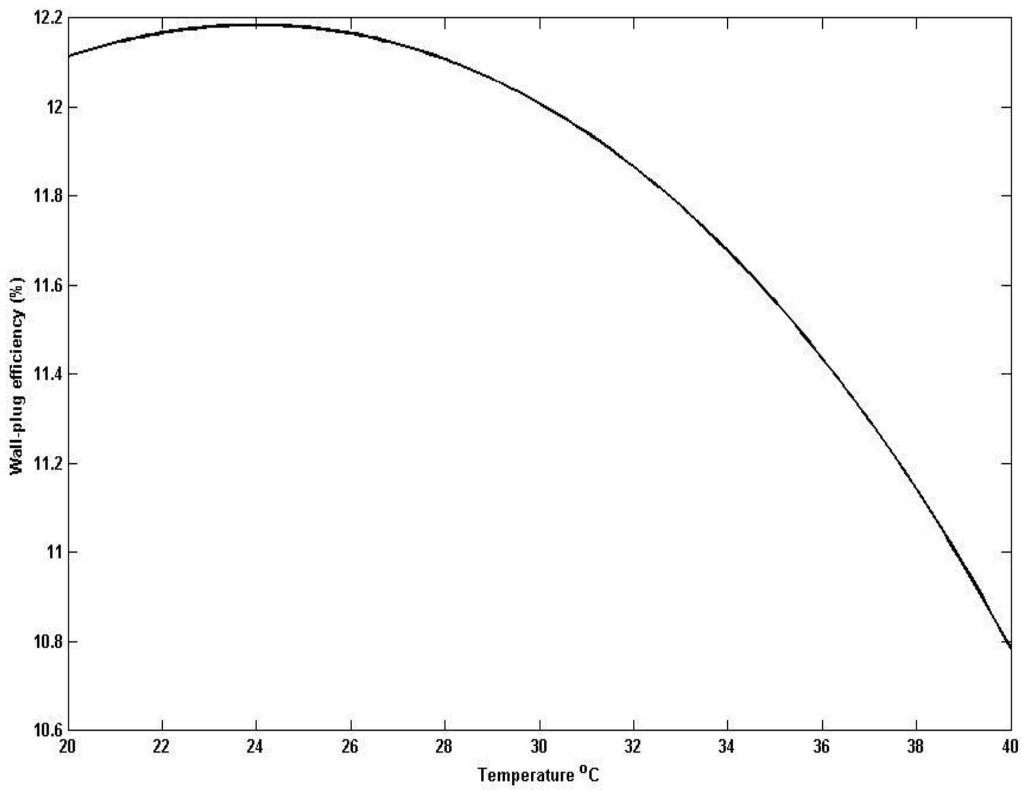

Figure 9. Variation of wall-plug efficiency with temperature.

studied in association with temperature rise and interpreted in terms of the parametric dependence of the device for the optimization for high power output. The main reasons for the decrease of the WPE are the excess voltage loss and internal waveguide optical loss. These effects may help for optimization of the most efficient device for high power output even though there is a trade-off between these factors.

REFERENCES

Bai Y, Bandyopadhyay N, Tsao S, Selcuk E, Slivken S, Razeghi M (2010). Highly temperature insensitive quantum cascade lasers. Appl. Phys. Lett. 97(25):251104-3.

Behringer M (2007). High Power Diode Lasers, Technology and Applications, edited by F. Bachmann, P. Loosen, and R. Poprawe, Berlin Springer. ISBN. 978-0-387-34453-9.

Botez D (1999). Design consideration and analytical approximations for high continuous-wave power, broad-waveguide diode lasers. Appl. Phys. Lett. 74(21):3102-3104.

Botez D, Mawst LJ, Bhattacharya A, Lopez J, Li J, Kuech TF, Iakovlev VP, Suruceanu GI, Caliman N, Syrbu AV (1996). 66% CW wallplug efficiency from Al-free 0.98 µm-emitting diode lasers. Electron. Lett. 32(21):2012-2013.

Coldren L A, Corzine SW (1995). Diode Lasers and Photonic Integrated Circuits. Wiley, New York. pp. 52-55.

Demir A, Zhao G, Deppe DG (2010). Lithographic lasers with low thermal resistance. Elect. Lett. 46(16):1147-1149.

Diehl L, Bour D, Corzine S, Zhu J, Hofler G, Loncar, Troccoli M, Capasso F (2006). High-power quantum cascade lasers grown by low-pressure metal organic vapor-phase epitaxy operating in continuous wave above 400 K. Appl. Phys. Lett. 88(20):201115-3.

Jian W, Summers HD (2010). An efficient approach to characterizing and calculating carrier loss due to heating and barrier height variation in vertical-cavity surface-emitting lasers. Chin. Phys. B. 19(1):014213-0142135.

Kanskar M, Nesnidal M, Meassick S, Goulakov A, Stiers E, Dai Z, Earles T, Forbes D, Hansen D, Corbett P, Zhang L, Goodnough T, LeClair L, Holehouse N, Botez D, Mawst LJ (2003). Performance and reliability of ARROW single mode and 100 µm laser diode and the use of NAM in al-free lasers. Proc. SPIE. 4995:196-208.

Laikhtman B, Gourevitch A, Westerfeld D, Donetsky D, Belenky G (2005). Thermal resistance and optimal fill factor of a high power diode laser bar. Semicond. Sci. Technol. 20(10):1087-1095.

Li H, Towe T, Chyr I, Brown D, Nguyen T, Reinhardt F, Jin Y, Srinivasn R, Berube M, Truchan T, Bullock R, Harrison J (2007). Near 1 kW of continuous-wave power from a single high-efficiency diode-laser bar. IEEE Photon. Techn. Lett. 19(13):960-962.

Ma X, Zhong L (2007). Advance in high power semiconductor diode lasers. Proc. SPIE. 6824:682402-1.

Schmidt B, Sverdlov B, Pawlik S, Lichtenstein N, Muller J, Valk B, Baettig R, Mayer B, Harder C (2005). 9xx High-power broad area laser diode. Proc. SPIE. 5711:201-208.

Shan Q, Dai Q, Chhhajed S, Cho J, Schubert F (2010). Analysis of thermal properties of GaInN light-emitting diodes and laser diodes. J. Appl. Phys. 108(8):08504-8.

Suchalkin S, Westerfeld D, Donetski D, Luryi S, Belenky G (2002). Appl. Phys. Lett. 80(16):2833-2835.

Sze SM (1985). Semiconductor Devices. Wiley, New York.

Williamson R, Kanskar M (2004). Improving the efficiency of high-power diode lasers. Compd. Semiconductors Rev. 2:2.