Effect of stress on the temperature coefficient of solder-free mounted laser diode bars

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ABSTRACT

Variation of lasing wavelength with temperature is a key factor to determine packaging thermal resistance in laser diodes. Using proprietary mounting technology that clamps laser bars instead of using soldering material we can precisely control the stress applied on the laser bars. We experimentally demonstrate that uniaxial stress in the normal direction of the p-n junction (which results in tensile stress in the lattice) increases the temperature characteristic of laser diodes. We report a temperature characteristic raise between 10% and 50% under different stress conditions.

Keywords: clamping, stress, laser diode, temperature coefficient, temperature characteristic, solder-free, wavelength tuning

1. INTRODUCTION

Junction temperature is a critical parameter for diode lasers as it affects their lifetime as well as threshold current, output power and lasing wavelength. Industry demands for higher brightness diode sources result in increasing efforts to improve laser diode optical power, therefore posing new challenges to their cooling. Semiconductor manufacturers have made great efforts in order to increase electro optical efficiency by reducing series resistance and reducing threshold current while packaging techniques focus on reducing the thermal resistance and avoiding the side-effects of materials with different CTEs that could compromise the lifetime of laser diodes because of thermo-mechanical fatigue.

A substantially different mounting technique where the laser bars are clamped instead of soldered was successfully demonstrated in the early 2000s [1] and used since then by Monocrom S.L. Such technique relies on the application of uniaxial stress in the direction perpendicular to the p-n junction to ensure a proper electrical and thermal contact between the laser bar and the electrodes. Because of this clamping force the p-n junction suffers from tensile stress.

The effects of stress on the electro-optical characteristics of semiconductor lasers have been largely investigated almost since the invention of laser diodes [2]. It is well known that stress affects the threshold current, emission wavelength and degree of polarization [3].

Sources of stress on laser diodes are lattice mismatch and mounting stress [4]. Whereas commercial high power laser diodes are available with compressive and tensile strains (being compressive strain the most common one), mounting stress always results into compressive strain because of the mechanical properties of the materials involved, as shown in Table 1. Moreover, it has been reported that the main component of the packaging induced stress is applied along the width of the laser bar [5].

Table 1 Properties of materials typically involved in diode laser bar packaging *[5], [6]*

	GaAs	CuW	Cu
CTE (ppm/K)	6.4	6.5	16.5
Linear compressibility (%/GPa)	0.44		0.24
Thickness (mm)	0.13	0.35	7.65
Thermal conductivity (W/m·K)	44-55	170	398

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This work focuses on the experimental study of the effects caused by uniaxial stress along axis [001] caused by the clamping force created by the solder-less mounting technique.

2. EXPERIMENTAL SETUP

The laser diode bars are clamped p-side down between copper electrodes in a conductively cooled package. A small preload is applied on the laser bars to ensure they don't move, and the resulting module is mounted on top of a Laird UTX8-12 peltier device with a Q_c=68.5W. A mechanical setup allows the application of a controlled load on the diode laser bar (Figure 1).

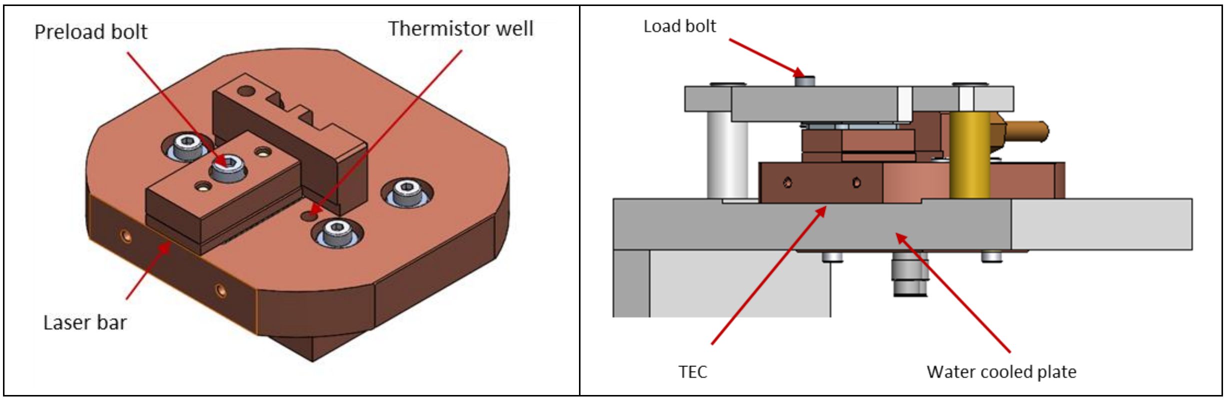


Figure 1 (a) Laser bar mounts and (b) setup used in the experiments

The pre-load and load forces are applied by means of screws and can be calculated from the following equations respectively:

$$M_A = F_{M,pl} \cdot \left(\frac{P}{2\pi} + 0{,}5775 \cdot d_2 \cdot \mu_G + \frac{D_{KM}}{2} \cdot \mu_K\right)$$

$$M_G = F_{M,l} \cdot \frac{d_2}{\pi \cdot d_2} + 1{,}155 \cdot \mu_G$$

Where M_A and M_G are the torques applied to pre-load and load screws, $F_{M,pl}$ and $F_{M,l}$ are the pre-load and load forces at the threads, d_2 is the thread diameter, P is the thread pitch, μ_G and μ_K are the friction coefficients of the thread and head of the screws and D_{KM} is the average friction diameter of the screw head.

The application of the pre-load and load forces on the bolts, produce a uniaxial compressive stress in the [001] direction [7] resulting in tensile stress along the width and length of the laser bar.

A temperature closed loop via a thermistor (NTC, R_{25}=10kΩ) located in the p-side electrode is stablished by means of a ILX Lightwave LDT-5900 temperature controller and the emission wavelength is monitored with a Avantes Avaspec-ULS3648-USB2-UA-25. The data from the different devices are acquired via a Keysight Technologies U2531A DAQ and controlled by a self-made software. A self-made laser driver generates the current pulses. Wavelength measurements are performed by means of an integrating sphere to ensure its value is a proper average of all the emitters in the laser bar.

In a second setup the laser module is placed in front of a polarizing beam splitter cube and both outputs are sent to identical Ophir FL250A-BB-50 thermal power meters so the degree of polarization (DoP) can be investigated as:

$$DoP = \frac{P_p}{P_p + P_s}$$

A third setup is set so the LIV curves in CW and the thermal resistance of the laser modules can be evaluated. For a DoP and LIV curves the laser module is operated in CW by means of aTDK-Lambda G-20-250 programmable power supply.

The laser bars used in this work have 19 emitters spaced 500µm, each of them having a stripe width of 150µm and a cavity length of 1mm, for a total power of 40W at λ=808nm. They are TE polarized, indicating a compressively strained QW [3].

3. RESULTS AND DISCUSSION

a. Degree of Polarization

According to the theory [8] the valence band degeneration due to tensile strain allows transitions from the conduction band to the light holes level, which result in an increase of TM polarized light. Our measurements outlined in Figure 2 are in accordance with theoretical prediction showing a clear reduction in the DoP with increasing clamping force. The current dependence of the DoP has also been investigated obtaining a degradation rate higher than that reported in the literature together with a slope change above 30A that cannot be clearly explained. According to Cassidy [9] shear strain induced birefringence causes changes in the DoP and angle for maximum transmission which are more noticeable for edge emitters than for central ones. If thermal induced birefringence could also occur, the combination of both might account for this behavior. Thus emitter-resolved measurements have to be conducted in this respect.

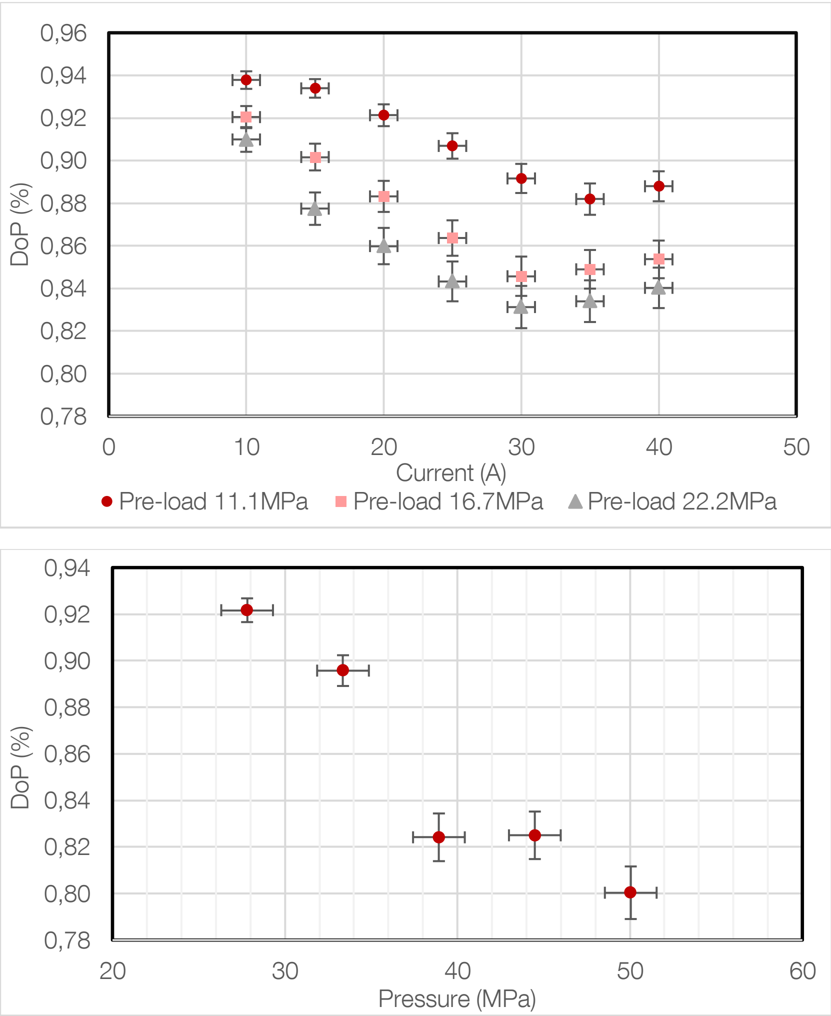
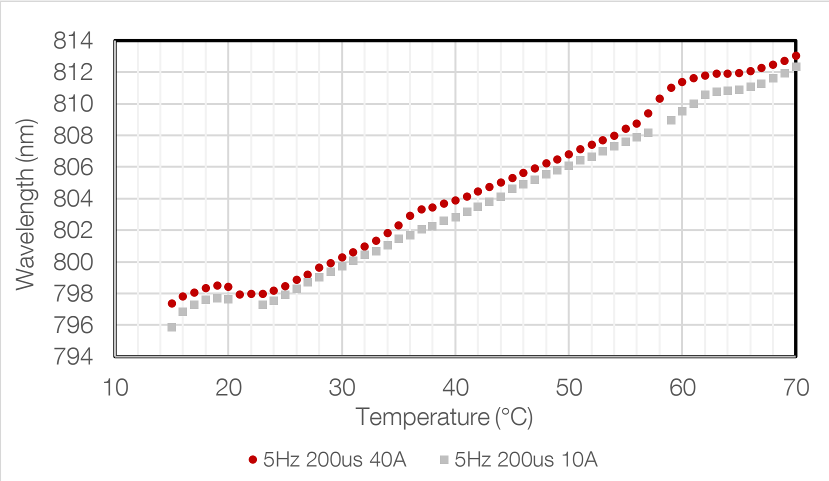


Figure 2 Degree of TE-polarization of (a) a laser (labelled SN2) bar under constant uniaxial stress along the [001] axis as function of the CW driving current and (b) another laser module (labelled SN3) at a constant driving current I=40A as a function of the load

b. Temperature tuning coefficient

To be able to properly assess the thermal resistance of the solder-less mounting technique precise measurements of the temperature tuning coefficient for the packaged bars are needed. In these measurements the temperature of the package is varied in steps of 1ºC, waited for stabilization and fifty wavelength measurements are averaged in each step. The temperature tuning coefficient is calculated as the slope of the measured peak wavelength versus the heatsink temperature.

The laser is operated under conditions that both ensure a reasonable signal to noise ratio in the spectrometer and avoid self-heating. Validation of the cold operating regime is done by repeating the experiment under different pulse conditions and currents for a duty cycle of 0,1% as shown in Figure 3.



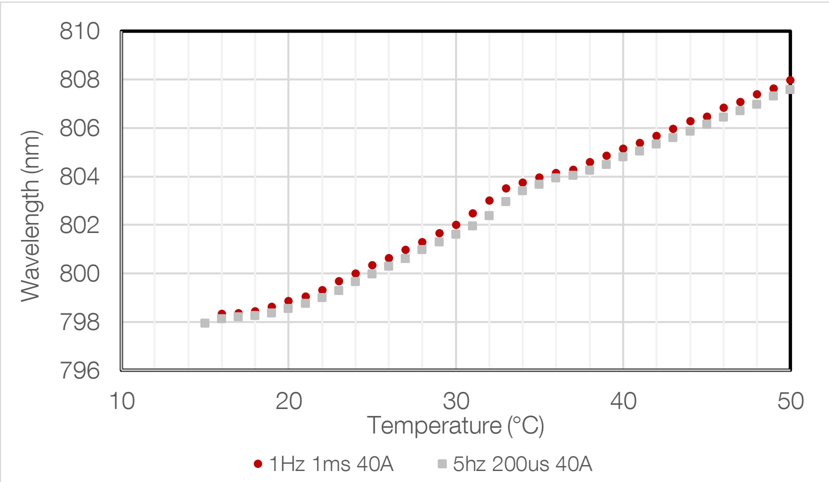


Figure 3 Wavelength tuning for different operating conditions. (top) compares the behavior when pre-load is set at 11.1MPa and the load is 0cN·m for driving currents of I=10A and I=40A while (bottom) compares pulse durations of t_p=200µs and t_p=1ms when the pre-load is 22.2MPa and the load is 0MPa

There is a clear sign that the wavelength tuning coefficient is not linear: kinks around 35°C and 55°C as well as a slope change below 20°C. This behavior was also reported by Vlasova et al. [10]. In their work they showed also that while a red laser diode had had a slope ${}^{d\lambda}/_{dT} = 0.12\,{}^{nm}/_{K}$ for T<285K and ${}^{d\lambda}/_{dT} = 0.21\,{}^{nm}/_{K}$ for T>290K a corresponding LED had a constant ${}^{d\lambda}/_{dT} = 0.16\,{}^{nm}/_{K}$ regardless the temperature which would be the shift due to pure energy gap change. Using the following equation, longitudinal mode-hops cannot explain the discontinuities (for the laser bars of study $\Delta\lambda \approx 0.09$nm) and no component affecting slope is identified:

$$\lambda_q(T) = \frac{2nL(T)}{q}$$

where λ_q is the emission wavelength of the LD, n is the refractive index of the material, q is the mode number and L(T) is the geometrical resonator length, which is linearly dependent with the CTE.

On the other hand, according to Tomm et al. [11] the wavelength shift is also affected by mechanical pressure on the semiconductor arising from packaging techniques. In their work with laser bars equivalent to those used in the present work they measured the pure thermal tuning contribution on the band gap change to be -0.48meV/K, which corresponds to a wavelength shift of 0.253nm/K while the mechanical pressure contributes with -0.08meV/K, which corresponds to 0.042nm/K. The pressure contribution is not even among the emitters of the laser bars, being zero on the edges and maximum for the central ones. Averaging the pressure contribution leads to 0.27nm/K commonly reported in the literature for this material.

In order to further investigate that hypothesis $d\lambda/dT$ curves have been obtained for different pre-load and load forces. All the laser bars under test show similar kinks as Figure 3: Between 25°C and 50°C the degree of linearity of the responses is high in all cases, therefore this temperature range has been used in order to calculate the slope and compare the data of all the samples.

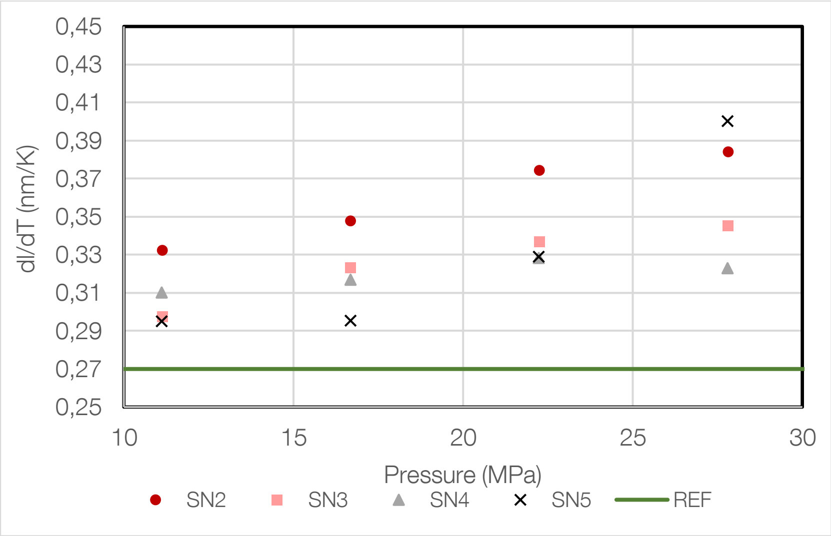


Figure 4 Wavelength tuning coeficient as function of the uniaxial load of four laser modules set at a pre-load of 11.2N/mm^2. The solid green line sets the reference for this kind of semiconductor.

The measurements presented in Figure 4 show a positive correlation between the wavelength tuning coefficient and the uniaxial stress applied on the laser bar indicating, as the DoP measurements did, that the stress in this clamping mounting technique is higher than in the soldered counterparts.

c. Thermal resistance

The wavelength tuning coefficients obtained have been used also to calculate the thermal resistance of the packaged laser bars in SN4 as it is the one showing less variation of the wavelength tuning coefficient with the force and at the same time shows the lowest values, so being a conservative approach for the calculations.

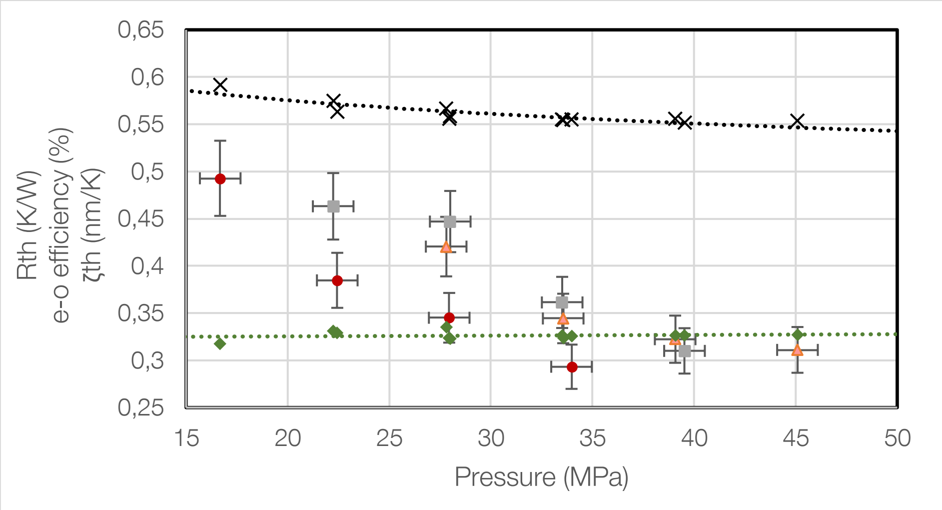


Figure 5 Thermal resistance as function of the uniaxial force applied. The three different series account for different pre-loads. Red circles are obtained with a pre-load of 16.67MPa, grey squares with a pre-load of 22.24MPa and pink triangles with a pre-load of 27.80MPa. Black crosses plot the electro-optical efficiency of the laser module. Green diamonds plot the wavelength tunability coefficient. Dotted lines are only eye guides.

The results are plotted in Figure 5 and show two interesting trends. From one side the thermal resistance reduction has an inverse correlation with the pressure which cannot be attributed to the variation of the wavelength tuning coefficient or the electrooptical efficiency. Therefore, the most valid hypothesis is that the thermal contact between the laser bar and the heatsink is improved with pressure. On the other side the thermal resistance when the pre-load was 16.67MPa is better than for pre-loads of 22.24MPa and 27.80MPa. This behavior is thought to be ought to an inhomogeneous distribution of the uniaxial force on the laser bar due to the application point of the pre-load.

The lowest thermal resistance achieved leads to a junction temperature T_j=31,7ºC for a dissipated heat of 40W. This experimental result is in very good agreement with the simulation results presented in Figure 6.

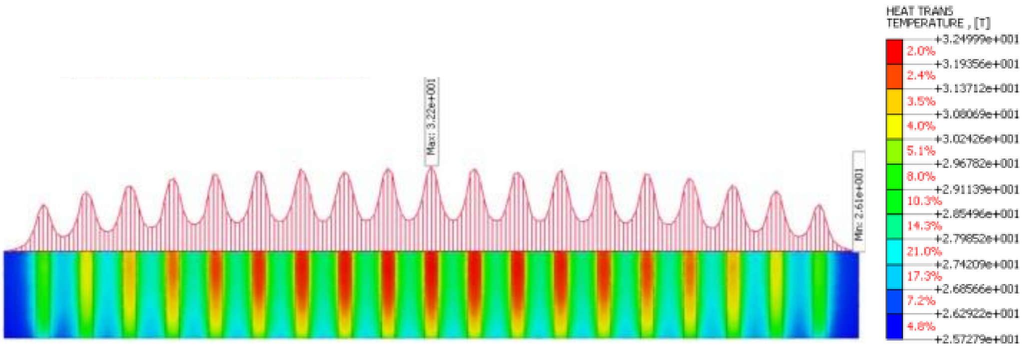


Figure 6 Thermal simulation of the laser bar under study performed with MidasNX. The thermal contact between the bar and the heatsink is assumed ideal. The laser bar has been modeled as a solid block of GaAs, 40W of heat being generated homogenously among 19 emitters directly in the interface between the bar and a pure Cu heatsink.

4. CONCLUSIONS

Uniaxial stress applied in the direction [001] results in a degradation of the degree of polarization (down to 83%) of the laser bar compatible with tensile strain in the p-n junction plane.

The wavelength tuning coefficient of the laser bars shows a positive correlation with the applied force and it is an average 21% higher than the reported 0.27nm/K.

The thermal resistance of the mounted bars reduces by 40% over a pressure range of 15MPa to 35MPa, which results in a junction temperature down to 29.2°C at I=40A and P_o=39.2W for a laser bar of 19 emitters, 30% fill factor, 1mm cavity length mounted on a conductively cooled Cu mount, which is in very good agreement with the simulations.

Further work will require emitter-resolved experiments to assess the stress distribution along the laser bar and its effects on the DoP, wavelength tuning coefficient and temperatures.

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