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Master in Photonics

MASTER THESIS WORK

Evaluation of tensile stress on the electrooptical charateristics of high power laser bar stacks

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Presented on date 8th September 2022

Registered at

Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona

Evaluation of tensile stress on the electrooptical charateristics of high power laser bar stacks

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Abstract. Mechanical uniaxial tensile strain affects the performance of high power laser diode bars (LDBs) inducing changes in the properties of the laser emission. Properties such as temperature tunning coefficient, far field divergence, polarization, threshold current and slope efficiency are altered. In this work we study how those variations happen and if the behaviour correlates with studies carried out to date. The experimental results seem to coincide with the stipulations regarding the variations depending on the position of emitters in the bars. However, when we variate the uniaxial tensile stress applied there are not correlations in our results, and therefore this question needs to be analysed in more detail.

Keywords: Laser diode bars, clamping, tensile stress, electrooptical characteristics.

1 Introduction

Laser diode bars (LDBs) have a wide range of applications covering telecommunications, solid-state laser pumping, material processing, etc. In a diode laser, a medium is crucial to provide optical gain by stimulated emission. The most common material used in the near infrared is gallium arsenide (GaAs). Another important element is an optical waveguide to confine photons in the active region. Finally, the optical cavity, with mirrors in both faces, generates resonance of the photons inside. Many different emitters are grouped together to form bars, whose scheme of standard dimensions is shown in Fig.1a. The systems in use are typically several diode laser bars with their beams coupled in to achieve high power emission, being about 120-150 W the maximum power that each individual bar provides in the near infrared (this is for bars with 20% fill factor, in the case of 50% fill factor bars can reach 250 W). Bars are composed of several individual single emitters integrated on a chip and each diode laser structure is made up of very thin active layers that are grown epitaxially on selected substrates. This process results in the appearance of several sources of stress, due to thermal and lattice mismatch between layers and substrates.

Packaging processes also introduce stress caused by the differences in thermal expansion coefficients between heat sinks and diodes. Different mechanical stresses affect the emission properties in terms of wavelength, threshold current, polarization, etc. The packaging of semiconductor diode lasers has traditionally been made with indium soldering on copper, but most recently also with hard-solders on CTE matched materials [1, 2]. One of the most critical factors of high power laser bars, as more and more output power is demanded, is the temperature experienced during operation, and that is why the packaging process with the heat sink is so relevant to the proper working. The tin-soldering technique shows poor reliability mainly due to the thermal coefficient mismatch between laser material and solder, while hard-soldering involves materials with poor thermal conductivity and limits the heat extraction capacity. Monocrom S.L patented a packaging technique in which laser bars are not soldered but clamped, by applying uniaxial stress perpendicularly to the p-n junction, achieving a good thermal and electrical contact with electrodes [3]. It causes the

appearance of tensile stress, directly controlled in a precise manner by the technique itself, but it affects to the emitted laser light [4]. In this project, the effects of the applied mechanical stress on the electrooptical characteristics of diode laser emission are studied.

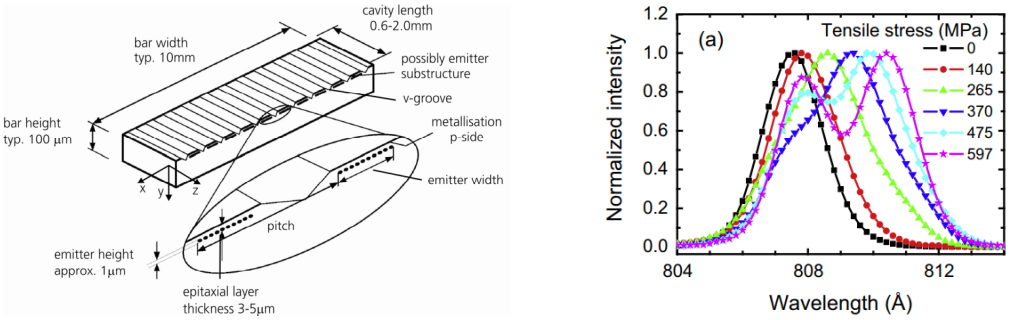
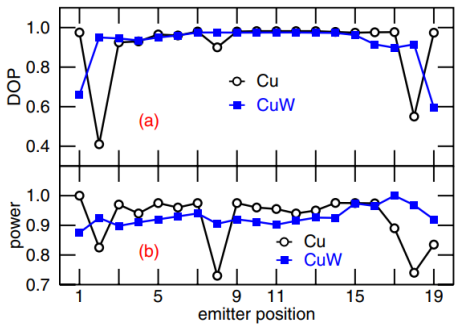


Figure 1: (a) Structure of a laser bar and typical dimensions [5]. (b) Change of spectrum of AlGaAs/GaAs diode laser with the tensile stress [6].

The effects of tensile stress in some features of laser emission have been historically studied in depth to optimize the performance of laser diode bars. Properties such as the emission wavelength, temperature tuning coefficient, degree of polarization and slope efficiency are affected by the mechanical stress applied. In terms of wavelength, the changes are mainly due to the affection that tensile stress causes on the semiconductor band diagram. The result is the decrease of the band gap when tensile stress is applied, what directly relates to an increase of the peak emission wavelength, as can be seen in Fig.1b. About how the behaviour of wavelength with temperature varies depending on the mechanical stress suffered, it is shown that temperature coefficient grows while tensile stress does, what means that the wavelength grows faster with increasing temperature for higher mechanical stress than for lower [7]. About the polarization of the laser light, it has been proved that mechanical stress induces the emergence of a secondary TM polarized mode coexisting with the main TE polarized mode, but in a lower proportion, and this leads to a drop in the degree of polarization (DoP) with the tensile stress [8]. Additionally, there are some mentions to the existence of a shear stress originated from packaging that mainly affects to the edge emitters, by creating a kind of birefringence, and resulting on an extra TM mode emission and DoP decay (see Fig.2a). Focusing now on the threshold current and slope efficiency, it has been observed that the higher the tensile stress applied, the higher the threshold current necessary for the diode start lasing (see Fig.2b), and the lower the slope efficiency in watts per ampere of the diode laser. Finally, the packaging induced tensile stress also affects to the beam divergence by increasing its angle as the stress build up [9]. All those variations of laser light properties with mechanical stress are so relevant for the manufacturing process in order to achieve the exact behaviour of the emission light desired, and knowing the exact effects can help to prevent manufacturers from developing undeperforming laser bars.

In this project, we experimentally measure the effects of the uniaxial tensile stress, resulting from laser diode bar non-soldering packaging technique, on the emission light and beam features mentioned above. We try to elucidate if Monocrom's bars behave as expected according to the literature and try to find the most plausible explanation in case they do not. The study has been made emitter by emitter in order to know the affections that the stress causes in its individual emission. In the next section the experimental development followed will be presented, in the third section results obtained will be shown and discussed, and finally some conclusions will be exposed.



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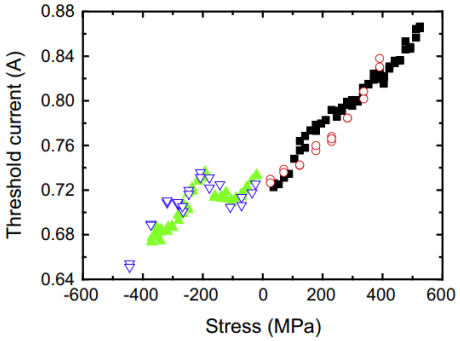


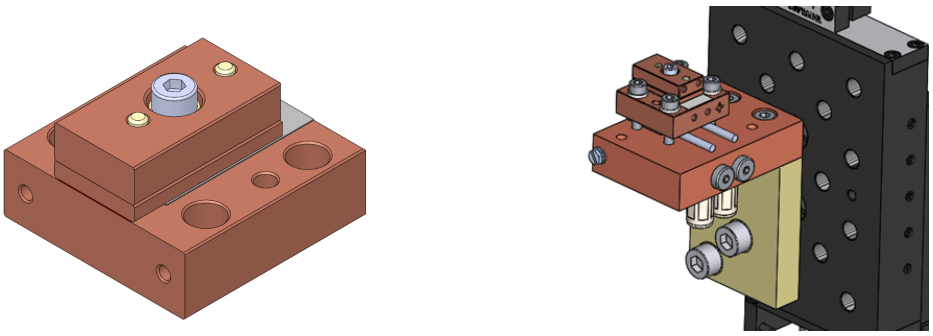
(b)

Figure 2: (a) DoP and power by emitter of Cu and CuW laser bars depending on its position in the bar [9]. (b) Change of AlGaAs threshold current as a function of the external tensile stress applied [6].

2 Experimental setup

This experiment focuses on analyzing how the mechanical tensile stress affects the laser emission of each individual emitter that a bar contains. To do that, different clamping forces are tested in order to have different values of mechanical stress to analyze the behaviour. The laser stack in use is a GaAs diode laser, consisting of only one bar with 10 individual emitters, each 100 microns wide, a pitch of 1 mm, and a resonator length of 4 mm. The nominal emission wavelength is 900 nm, and the power that the bar provides at 100 A is about 100 watts (10 watts per emitter). The design for the one bar stack is shown in Fig.3a, where it can be seen the screw to clamp it with the proper torque, and the emission facet in between the two mounts. The main part of the setup, that remains unchanged along all the different experiments, is the stack support tool (see Fig.3b). It consists of a base on which the stack is screwed, with two tube connectors at the bottom to allow the tool cooling by means of a chiller. In between laser and the base a peltier cell or thermoelectric cooler (TEC) is placed to control the temperature of the laser bar, and it is cooled by the support tool, so that the laser results to be passively cooled, with its temperature monitored by a NTC. The base is joined to a three axis positioning element, that allows to move the stack in three dimensions. A driver provides power supply to the laser, with a module designed by Monocrom that allows pulsed mode operation with the help of capacitors, in which we are going to make the whole experiment. The by emitter analysis is done by placing a cooled slit extremely close to the facet that blocks the beams coming from all other diodes excepting the one of interest, which pass through it. Those are the items that are going to be displayed with the same configuration in all different testing that will be done. There have been deployed four different setups, each for one group of measures that will be taken. The first setup measures the temperature tuning coefficient, the second setup focuses on the beam divergence of the slow axis, the third one characterises the output power versus input current, and the fourth one is used for the study of polarization.

The first experiment to be carried out is the temperature tuning coefficient test. We proceed by placing in front of the laser assembly simply an optical fiber connected to an spectrometer, that will measure exactly the peak wavelength at every moment. The tests will be conducted, by turning the screw with a torque spanner, at four different torques: 60 cNm, 80 cNm, 100 cNm, 120 cNm. A LabView program performs a raise of temperature from 15ºC to 60ºC, with the help of the TEC, while the spectrometer registers the peak wavelength at each point. Then, just by performing a linear fit of the obtained curve of wavelength in front of temperature, the temperature coefficient in nanometers per kelvin is obtained. The working operation mode for this case is pulsed mode with 5 Hz pulse frecuency, 100 μs, and 40 A current. In this mode, only about 200 mW are reached, so that the heating effects can be neglected. This process will be repeated for each one of the emitters in the bar, and the data of each of them is analysed.



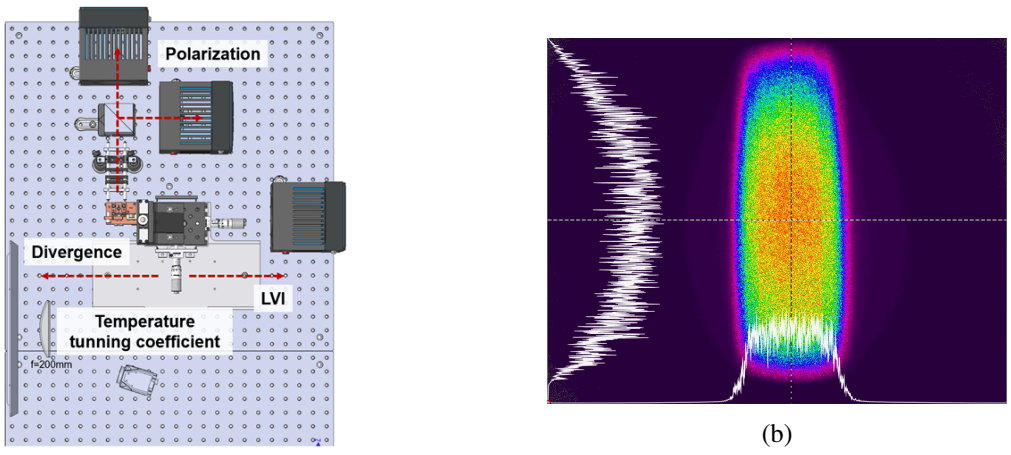
(a) (b)

Figure 3: (a) View of the mount design for one bar laser stacks. (b) Scheme of the structure used to support and move the laser bar (located on the base tool).

The divergence measurements consist of placing in front of the laser a plano-convex lens of 20 cm focal length, and just behind it at the focal distance put a screen (see Fig.4a). A CCD camera pointing to the screen will collect the beam shape data (see Fig.4b) and with just some data treatment it will be possible to get the angle in the far field of slow axis divergence for a given percentage of energy. The process is carried out for different torques and emitters, and in 50 Hz frequency, 200 μs width pulsed mode at 100 A total current (10 per emitter). This method is different from the conventional divergence measurement method that involves the calculation of the beam propagation ratio M^2, but according to [8] this is also a valid method. The divergence can be calculated as follows:

$$\theta_\sigma = \frac{d_{\sigma f}}{f} \tag{1}$$

where f is the focal distance of the aberration-free focusing element and $d_{\sigma f}$ is the beam width at its focal plane. The beam width is calculated by performing a super-Gaussian fit to the data provided by the camera.



(a) (b)

Figure 4: (a) Setup scheme for the different experiments. (b) Laser beam shape captured by the CCD camera.

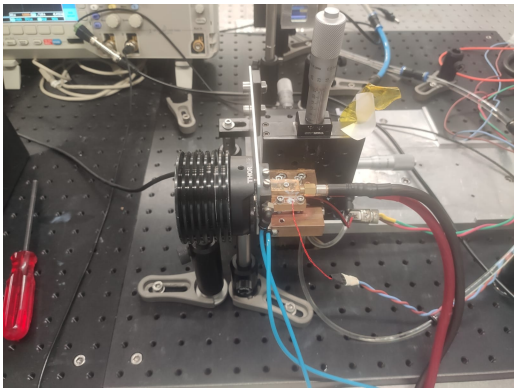
The power characterisation is done just by switching on the laser and pointing it to a power meter (see Fig.4a, LVI label), getting different power values for various current values. In this experiment the characterisation is done in pulsed mode (50 Hz and 500 μs) instead of the typical continuous mode way, so that it is expected to avoid thermal effects on LI curves. With the power-current

values a linear fitting can be performed to obtain the slope efficiency of the diode laser and the threshold current of operation. Each one of the emitters will be characterised for different tensile stress applied.

The study of polarisation includes two different setups for two different tests. The first setup is shown in Fig.5a and is used for the study of the Degree of Polarisation (DoP) of the laser beam. The elements in use are a power meter and a linear polariser, and the process consists of turning the angle of the linear polariser in order to find the maximum and minimum intensity arriving to the power meter. The calculation of DoP is done according to the following equation:

$$DoP = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{2}$$

This procedure is performed in pulsed mode (50 Hz, 1 ms), with 100 A of total current, and is repeated for the different emitters and torques. For the study of the state of polarization a quarter waveplate is added to the setup (see Fig.5b). The aim is to find out whether there is one either linearly or elliptically polarised mode or whether there are two orthogonally polarised modes. The method followed consists of fixing the waveplate fast axis at different angles (0, 30, 45 and 60 degrees) and find the maximum and minimum intensity (and its angles) by rotating the polariser. In this case, the laser is also in pulsed mode but the duty cycle must be increased to have enough intensity in the power meter, so we work with pulsed of 50 Hz and 2 ms, and with 110 A of total current.



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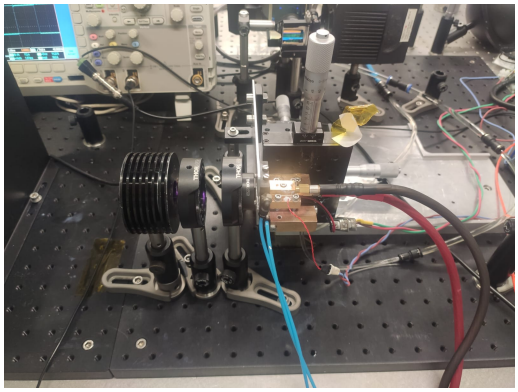


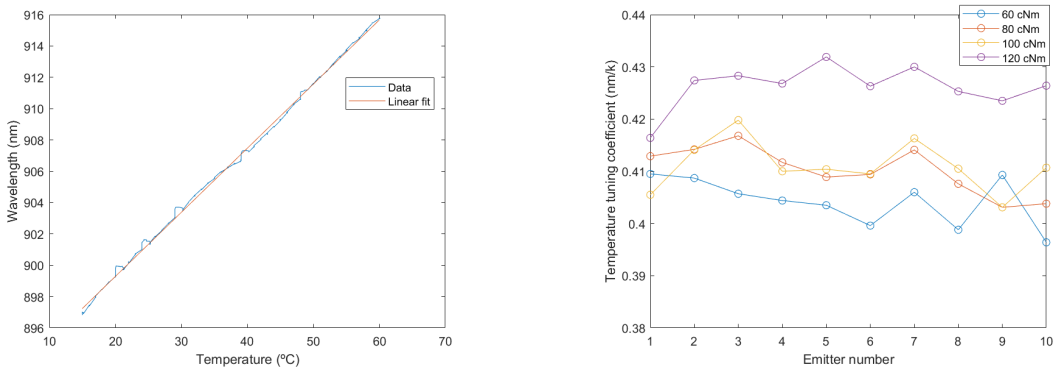
(b)

Figure 5: (a) Picture of the setup used for the DoP study, consisting of (from left to right) a power meter, a linear polariser, and the cooled slit that separates those elements from the main laser assemble. (b) Picture of the setup used in the study of the state of polarisation, which again contains a power meter and a polariser, but now a quarter waveplate is added between the polariser and the slit.

3 Results and discussion

In this section, the results achieved in the different experiments are shown and analyze, with a discussion about whether or not they meet the expectations, and with possible reasons for non-compliance and explanations of the expected behaviours. There are some behaviours that are well known but have not proved explanations, so that the only thing we can do is to expose the more likely and accepted hypothesis that have been made by researchers in the field.

The first results to be analysed are those of the temperature tuning coefficient. The measuring process is based on externally heating the laser bar to observe how the change in emission wavelength happens. The data of wavelength and temperature are collected by the LabView program, and for one emitter and one heating cycle from 15ºC to 60ºC they are represented and adjusted such as in Fig.6a. The slope of the linear fitting gives the temperature tuning coefficient, which in all studied cases (emitters and torques) is around 0.4 nm/K or slightly above. We can see how there are some small change peaks of wavelength with temperature that could be due to the non-homogeneous heating process, and they can introduce some errors that will be considered. Another hypothesis is that the cavity length changes with the temperature causing longitudinal mode jumping. In the figure 6b, the coefficients for each emitter and different torques are shown. It has been estimated and error of 0.01 nm/k, that comes from the experimental procedure itself and from the statistical treatment, but it has not been included in the graph to avoid over-information. It can be seen in the graph how the temperature coefficient seems to grow with the mechanical stress, what is suitable with the literature. The change of wavelength with temperature is mainly due to the dilatation of the semiconductor lattice and to the dependence of electronic interaction with temperature, both affecting the band structure. The mechanical tensile stress also affects the band structure by reducing the bandgap, which favours a faster change of wavelength with temperature. About the emitter position in the bars, simulations show that edge emitters suffer more stress and therefore should have higher coefficients, what cannot be directly appreciated in the graph. In fact there are not significant differences along the bar beyond some undetermined variations, and it could be due to the insufficient experiment accuracy. Another hypothesis could be the appearance of a different mechanical stress in the edges, called shear strain, that could have a different affection to the temperature tuning coefficient.

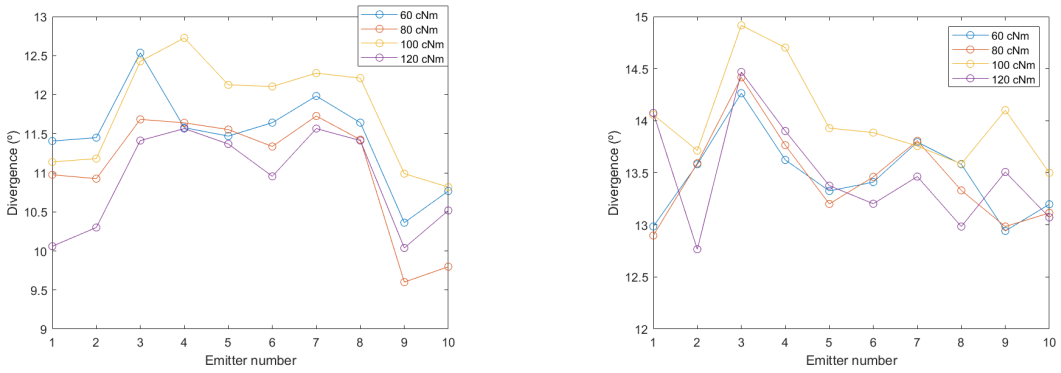


(a) (b)

Figure 6: (a) Example of wavelength versus temperature data for one emitter and one heating cycle, with the linear fit to the data. (b) Graph that shows the temperature tuning coefficient for each emitter and torque (emitter number 1 corresponds to the right edge and number 10 to the left one).

Now the results of divergence measurements are shown. The divergence measurement method is quite simple, but is extremely sensible to variations in the conditions of the experiment. This is why an error of 1 degree is estimated for each one of the measurements, coming from both the experimental part and the data treatment. The results of the beam angle of divergence for the different emitters and torques, and both at FWHM (Fig.7a) and for the 95% of the energy, are shown (see Fig.7b). The graphs show divergences between 10 and 15 degrees varying for the various cases. It is difficult to extract a pattern of behaviour from the data, because the results variate quite randomly. It is expected that the angle of divergence increase with the tensile stress, due to reasons that are not clearly understood. Among the most widely considered hypothesis is that the mechanical stress causes changes in the refractive index of the active medium, and this implies variations in the propagation of light along the cavity and can affect to the beam shape, so that the angle of divergence can be affected. In Fig.7a we can observe how the divergence

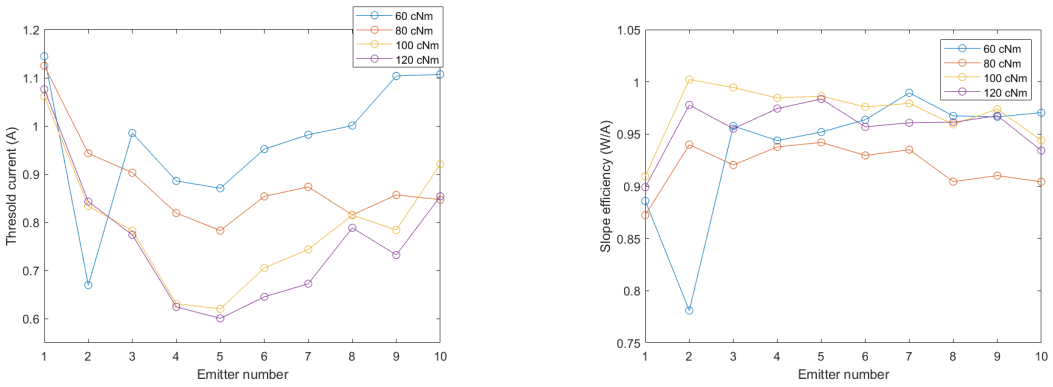
is lower at the edges than in the center of the bar, despite having more mechanical stress in the edges. This could be explained because the mechanical stress increases the divergence angle but also changes the beam shape to a more Gaussian shape, so the divergence at FWHM of an edge emitter has been narrowed respecting to a centered emitter. Those two effects (divergence growth and Gaussian shaping) are compensated in Fig.7b and no systematic variations can be observed between emitters. It can not be appreciated in either of the two graphs explainable variations between different torques, that are supposed to be clearly identifiable. Measurements of different torques have been done in different moments without keeping the setup unaltered, so it could have affected to the results. Also the method used may not be as precised as required for detecting the real changes in the divergence. Further studies with improved conditions should be done to try to reach more reliable conclusions. The calculation of the beam propagation ratio by measuring the beam width at different positions is highly recommended to achieve the proper accuracy.



(a) (b)

Figure 7: (a) Divergence angle at FWHM for each emitter and with different tensile stresses applied. (b) Divergence angle of 95% of the energy for each emitter and with different tensile stresses applied.

The power characterization of laser emission allows to easily get, just by measuring some power values for given currents, the threshold current and the slope efficiency of the laser, which are two important parameters to be known. However, it has certain limitations in terms of the reliability of the measures, mainly due to the power meter sensitivity to minimal changes in the setup or its own fluctuations in the measured values. The pulsed mode operation can also introduce some challenges, not being the usual mode to do the characterization, and having to correct the power values measured to a 100% duty cycle. This is why important error margins of 0.1 A for the threshold current and 0.1 W/A for the slope efficiency are considered, despite not including error bars on the graphs for clarity reasons. The results are shown in Figures 8a and 8b, in which the variations of slope efficiency and threshold current with the torque and the position in the bar can be seen. The data show again some patterns between emitters according to their location rather than the stress they experience. The edge emitters suffer more tensile stress than those in the center of the bar, what according to literature implies an increase of threshold current mainly due to the decrease of quantum well and therefore the reduction of carriers confinement. This is what we observe in our results with the by-emitter analysis, but not fulfilled when different torques are studied. We believe that another more rigorous experiment, without setup alterations, must be perform before claiming that the expected behavior is not actually observed. About the slope efficiency, the tensile stress reduces the slope efficiency, as a consequence of the increase of the so-called leakage current due to the rise of the non-usable surface. The leakage current also contributes to the threshold current growth. In the data collected it can be slightly appreciated lower slope efficiencies in the edges, despite not being able to draw conclusions when different strains are tested.



(a) (b)

Figure 8: (a) Threshold current per emitter in amperes for the laser operation evaluated for different tensile strains. (b) Slope working efficiencies for each individual diode in watts per amperes.

The study of the degree of polarisation (DoP) is an important part because it is necessary to understand how it is affected by the mechanical stress. The measurements are done just by placing a linear polariser before the power meter, so it is important working in pulsed mode to increase the duty cycle up to 5% for reaching the minimum power value detected by the power meter. The DoP obtained in each case is shown in Fig.9a. The error interval estimated is about 0.1 considering how both the power meter fluctuations and the sensitivity of measurements to rotations in the polariser affect to the final value. It can be seen how the DoP is lower in the edges while again there are no reasonable conclusions for the different torques. The fall of the DoP in the edges can be explained by the strong mechanical stress suffered. It causes a splitting of heavy and light holes valence bands that results in not only TE polarised transitions, but also TM polarised ones, being the DoP affected. It can also be appreciated an abrupt drop in the DoP for emitter number six, which is blamed on a damage in that individual emitter affecting to its polarisation. The drop of the DoP of polarisation in the edges has also something to do with the emergence of a different strain called shear strain, that affects mainly to the ends of the bar, intensifies the appearance of TM modes, and can induce some birefringence that may affect to the state of polarisation. The study of the state of polarization aims to determine how is that induced birefringence. The key to quantify the birefringence is to evaluate the state of polarisation of each emitter using the waveplate and the polariser. It has been tried to be measured for different torques, but to simplify the understanding of results we focus in only one of them (120 cNm), also given the scarce information obtained in the previous experiments by performing it for various. It can be claimed from the DoP experiment that the state of polarisation is not a singular linearly polarised mode, because the measured minimum power is not zero for any polariser angle. When using a quarter waveplate, we can also reject a circularly polarised mode, because if it was the case, the quarter waveplate with its fast axis at 45 degrees would transform the beam to linearly polarised, that would be blocked for some angle of the polariser, and it does not happen in the practice. If we take a look at the linear polariser angles that give minimum power (angles of maximum are approximately 90 degrees smaller), it is interesting to observe (see Fig.9b) that in the case of 0, 30 and 60 degrees of the fast axis quarter waveplate the angles are quite similar. For 45 degrees of quarter waveplate angle there seem to be several variations at the edges that may indicate a different polarisation state, and therefore the appearance of birefringence. One should be cautious with that statements because the error margins are important both for the power and the angles, and it is not clear this behaviour and its possible explanation. In Figure 9c, it is curious to see the maximum and minimum power and how at 45 waveplate degrees maximum and minimum does not coincide as it could be expected. If we supposedly have two orthogonal lineal polarisation mode, TE more present than TM, they should become circular after passing through the waveplate at 45 degrees, and no maximum and minimum in power should appear after crossing the linear polariser. The hypothesis is that this maximum and minimum continue appearing because both modes are not perfectly coherent between them,

but has nothing to do with non-linear polarisations of the initially emitted modes. Anyway, the study of the state of polarisation has to be done in more detail and with more sophisticated setups to get strong conclusions about the actual state of polarisation of the laser emission and about the possible birefringence. The addition of a third polarisation element to the setup, maybe an analyser or a half waveplate, could help to get a better understanding of the polarisation state.

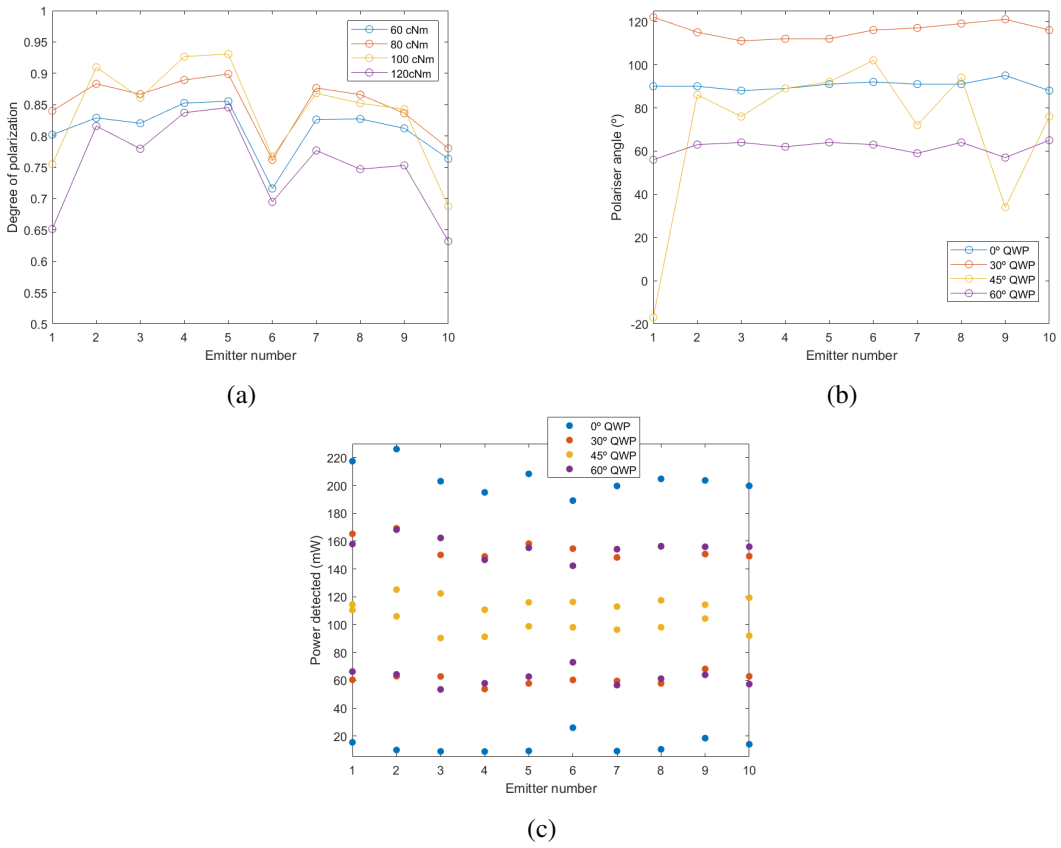


Figure 9: (a) Degree of polarization (DoP) of each emitter and for different torques. (b) Angle of the linear polariser for which the power measured is minimum, for different emitters, and also for different angles of the quarter waveplate fast axis (120 cNm case). (c) Maximum and minimum power measured for each emitter and for different angles of fast axis quarter waveplate (120 cNm case).

4 Conclusions

To summarize, in this work we have studied the effects of mechanical uniaxial tensile stress in the emission properties of high power laser diode bars, analysed for individual emitters. We have focused in the wavelength temperature tuning coefficient, the far field slow axis divergence, the slope efficiency, the threshold current and the polarisation. We have reported expected variations of those parameters according to the position of each emitter on the bar, providing theoretical explanations or hypothesis for these behaviours. Some properties such as divergence or polarisation has to be analyze in more depth as we have not obtained easily argued results. In the case of the divergence, it does not increase in the edges as expected, being the most likely reason reported a change in the beam shape. About the polarisation state, it is difficult to conclude from the results with certainty the actual state of polarisation and relate it with tensile stress and a possible birefringence. More analysis has to be carried out for a complete understanding, but we have confirmed the coexistence of two orthogonally polarised modes. Also there are some indications of possible birefringence that should be confirmed in future works. About the study of the properties for different clamping forces, we have hardly obtained significant and reasonable results apart from the temperature tuning

coefficient, that seems to behave as expected. This is probably because the different experiments were all carried out for one torque before switching to another torque and repeating again all the experiments, therefore the conditions would have been slightly modified. That is why the tests have to be repeated trying not to alter the setups.

5 Acknowledgements

First of all, I am very grateful to Monocrom S.L. for giving me the possibility to have a very enriching experience by allowing me to do my master thesis with them. I would like to thank Carles Oriach for coordinating my stay at Monocrom and for his help and guidance in carrying out my work. I would also like to thank Crina Crojocaru for her supervision as my tutor at the UPC and her help with some of the doubts I had. Finally, I would like to thank my colleagues at Monocrom for their day-to-day help that made my work and my stay at Monocrom easier.

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