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LOW-TEMPERATURE CHARACTERIZATION OF A 1.55- μm MULTIPLE-QUANTUM-WELL LASER DOWN TO 10 K

Emmanuel Mercado

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**LOW-TEMPERATURE CHARACTERIZATION OF A 1.55- μm
MULTIPLE-QUANTUM-WELL LASER DOWN TO 10 K**

by

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THESIS

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DEDICATION

Para Lilian, mi amada esposa, cuya vehemencia y devoción sustentaron este sueño.

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LOW-TEMPERATURE CHARACTERIZATION OF A 1.55- μm MULTIPLE- QUANTUM-WELL LASER DOWN TO 10 K

by

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ABSTRACT

A ridge-waveguide 1.55- μm semiconductor laser with a multiple-quantum-well carrier confinement structure was characterized from room temperature down to 10 K. The temperature dependence of important laser parameters, such as threshold current, differential efficiency, emission wavelength, and series resistance, extracted from conventional L-I-V and spectral measurements, is presented and analyzed. The results indicate that a diode laser designed for room-temperature operation can perform surprisingly well at cryogenic temperatures.

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CHAPTER 1. INTRODUCTION

The temperature dependence of the operation parameters of semiconductor lasers has been a subject of intensive research since double-heterostructure diode lasers were proposed in 1963 [Kroemer 1963]. These efforts eventually led to demonstration of room temperature operation of injection lasers in 1969 [Kressel 1969], [Hayashi 1969], [Alferov 1969], a breakthrough that allowed these devices to find diverse and vast applications in modern technology. Nowadays, the continuing need for enhanced performance in advanced signal processing systems and applications has made the implementation of optical data links within cryogenic environments very attractive. Superconducting circuits provide processing speeds that far exceed the present state of conventional electronics. For example, superconducting single-flux-quantum (SFQ) circuits can operate as logic and memory circuits at clock frequencies over 100 GHz with extremely low power [Likharev 1991], [Likharev 1993], and ultimate speed of 770 GHz has been demonstrated experimentally [Chen 1993]. The main bottleneck for realizing large-scale systems utilizing SFQ circuits is the thermal interface between liquid helium

Figure 1. Application of an optical data link for interconnection to cryogenic systems.

and room temperature environments for optical data transport from 4 K to 300 K. An illustration of this and other similar applications is showed in Fig. 1. As can be seen from the figure, the superconducting system must be thermally isolated from the environment to minimize the expenditure of energy on keeping the temperature constant.

Interconnection to the system using electrical interfaces can have a significant impact on the energy budget, since these interfaces require physical contact between the system and the environment. In contrast, an optical link does not impose this requirement and, therefore, avoids the possibility of heat injection into the system through heat conduction mechanism.

Based on the analysis of prospects for ultrafast, low power data transmission at room temperature, it has been suggested that active laser transmitters offer better prospects for satisfying stringent thermal requirements for cryogenic data links than external modulators [Mercado 2013]. Although early diode lasers were demonstrated at cryogenic temperatures and were shown to exhibit an enhanced performance in this temperature range [Katz 1985], their use in practical systems is still mainly limited to room temperature applications. As a consequence, availability of device performance parameters for cryogenic operation is very limited, and such parameters are virtually nonexistent for commercial devices. The purpose of this work was to experimentally explore the main diode laser operating parameters at low temperatures by systematically applying well-known characterization techniques conventionally used at room temperature.

Fig. 2 depicts the laser characteristics considered in this work. The L - I characteristic describes the relation between optical output power and injection current for a diode laser. The threshold current and external differential efficiency can be extracted from this information. In addition, it has been suggested that the transparency current can also be extracted from this relation [Mercado 2013]. A detailed account of this procedure is included in this work. The estimation of the external differential efficiency also requires knowledge of the emission wavelength. This parameter is not well defined for multi-mode lasers. This uncertainty is reduced by estimating the external differential efficiency from the above-threshold region of single-mode operation. An algorithm based on derivative analysis of the L - I characteristic is proposed for indirect determination of such range. The spectral power density was also measured in this range for determination of the wavelength. The V - I characteristic describes the relationship between the device voltage and current. The series resistance and ideality factor were extracted from this information.

Figure 2. Laser characteristics considered in this work for extraction of laser parameters.

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CHAPTER 2. EXPERIMENTAL TECHNIQUE

Accurate characterization of diode lasers from room temperature down to cryogenic temperatures imposed important additional challenges in comparison with room temperature measurements. The ability to achieve a very good temperature stability and control was, perhaps, the most critical requirement. It also turned out to be the most difficult parameter to control. Also, since the laser had to be operated inside a cryostat, access to output light was very limited and, together with the highly divergent beams typically observed, adequate optics for collimating and handling such beams were necessary.

In addition, it was also important to obtain very fine and accurate measurements of the device current and voltage characteristics. Noise and drift in the data would very easily prevent fitting to the simplified electrical model proposed in this work in the sub-threshold region of operation. This also required characterization of the device in very small current step increments.

Fig. 3 depicts the schematic of the experimental setup used in this work. The diagram exhibits the most important components in the system. The independent variables on this setup are temperature and current. The dependent variables were optical power, voltage, and spectral power density. The functionality of each component will be analyzed in the next sections.

2.1 Laser Selection

In this work, a COVEGA FPL1055C 1.55- μm MQW ridge-waveguide Fabry-Perot high-power laser was electrically and optically characterized from room temperature down to 10 K. Fig. 4 shows the manufacturer's drawing of this laser. Among other commercial devices, the FPL1055C was chosen due to its availability in a chip-on-submount (COS)

Figure 3. Experimental setup diagram for characterization of diode lasers from 300 K down to 10 K.

package. This minimalist package was preferred because it was not known upfront whether a fully packaged device could withstand the thermal stress arising at temperatures well below its specified operating temperature range. Although it was also uncertain whether the laser chips themselves would survive such extreme conditions, it was anticipated that packaging failures were far more likely to occur even at moderately low temperatures. In addition, it was of utmost importance to minimize the thermal resistance between the device and the heat sink in order to achieve the best possible temperature control in the device itself. For high-power lasers, such as the FPL1055C, this consideration is usually addressed by choosing the best materials and processing for chip bonding the device to the submount in order to optimize the device performance. In addition, the FPL1055C submount was fabricated on AlN, a material with a very high thermal conductivity frequently used for efficient heat extraction.

2.2 Laser Packaging

2.2.1 Heat Spreader

Copper is one of the best heat conductors found in nature. It exhibits an impressive thermal conductivity of 397 W/m-K, making it the material of choice for heat spreading applications. However, submount attachment to bare copper is challenging for two

Figure 4. FPL1055C drawing as per manufacturer's data sheet.

reasons. The first one is the existence of a thick layer of oxide at copper surface. Copper oxide layer thickness is estimated from the oxide film thickness at which the regime of oxide formation transits from fast ion diffusion process dominated by electrostatic gradients to a slower ion diffusion process ruled by ion vacancy gradients between the metal and the oxidized layer [Ebisuzaki 1985]. The transition occurs around a thickness of 102 to 103 Å [Ebisuzaki 1985]. Under common storage conditions, it is estimated that this film typically grows to ~ 1000 Å, although it can reach 1 µm or more if the metal is exposed to oxygen for a long time [Ebisuzaki 1985]. The oxide layer can considerably decrease the heat conductivity through the joint if not removed. The second problem associated with the use of copper as a heat spreader is the potential formation of intermetallics due to copper diffusion into the solder material. Copper dissolves in indium or indium-rich solders by solid state diffusion, forming an intermetallic product. The reaction can readily occur at room temperature, but higher rates are observed at higher temperatures [Barnard 1974]. Nonetheless, in a study done with energy dispersive X-ray analysis (EDAX) for analyzing intermetallics at the interface of copper and InPb solder, no intermetallic products were found at 80°C [Seelig 1995]. At 125°C, some intermetallics were formed, but in quantities similar to standard SnPb solders [Seelig 1995]. These results indicate that intermetallic formation is not an issue as long as joint temperature is kept under 80°C, which was the case in our experiments.

Upon consideration of the information provided above, it was decided to use bare copper for packaging with no specialized finish. Prior to soldering, the oxide layer was removed from the heat spreader by immersion in a strong acidic solution of 60% H₂O, 20% HNO₃, and 20% H₂SO₄, followed by a rinse in distilled water. The process efficiently removes

the pervasive copper oxides. As stated before, the process of formation of intermetallics with indium or indium-rich solders was not considered important in our particular case. These intermetallics were observed on other packages that require heating the heat-spreader to $\sim 150^{\circ}\text{C}$ during chip bonding. For these, proper metallization with Ni/Cr/Au was recommended [So 2000]. Since for the FPL1055C no further processing was required for chip bonding (COS package commercially available), it was observed that intermetallics did not form in a significant amount even after 1 year.

2.2.2 Submount Bonding

It was desired to solder the submount to the copper heat-spreader using indium or indium-rich solders in order to simultaneously provide an outstanding thermal performance and the ability to absorb mechanical stress arising from thermal coefficient of expansion (TCE) mismatch at the junction between AlN and copper. Pure indium and indium/lead solders were considered in this case. Table 1 compares some of the most important thermal and mechanical properties of InPb and In. As can be observed in the table, InPb solder has both a higher tensile and shear strength than In and yet it is less brittle than pure indium due to a higher ductility. Also, the TCE is almost the same for both solders. This is the reason why InPb solders have been recommended for soldering very rigid materials with high TCE mismatch [Seelig 1995]. Overall, it is clear that InPb is mechanically superior to pure indium, although its melting point temperature is significantly higher.

Property	InPb (50%)	In
Liquidus temperature [°C]	210	157
Solidus temperature [°C]	184	157
Thermal coefficient of expansion	27	29
Thermal conductivity [W/m-°C]	22	86
Tensile strength [psi]	4670	273
Shear strength [psi]	2680	890
Elongation [%]	55	22-41

Table 1. InPb vs. In solder thermal and mechanical properties.

Despite all benefits associated with InPb solder, the FPL1055C submount was not bonded to the Cu heat-spreader using InPb, since it was not known upfront what material was used for laser bonding. Since the melting point of InPb is higher than In, the latter was used in an attempt to prevent the reflow of such material. Indeed, the COS package was not affected by submount bonding at 160 °C using indium.

Preservation of the COS package metallization was also an important consideration for bonding to copper heat spreader. Indium or indium-rich solders effectively prevent gold scavenging in layers thicker than 50 μin (1.27 μm) [Seelig 1995]. In contrast, common solders, such as SnPb, will easily dissolve such layer, mostly due to the large solubility of gold in tin [Seelig 1995]. Thus, even though the actual thickness of the submount metallization layer was not known, it was anticipated that indium would help to preserve such layer.

Figure 5. COVEGA FPL1055C COS with high thermal performance package for characterization at cryogenic temperatures.

2.2.3 Package Assembly

The finalized package is shown in Fig. 5. Customized isolated contacts were provided for wire bonding and for soldering wires used for current injection and voltage sensing.

These contacts were pieces of Si wafers with gold metallization, mounted on small glass slabs. These were glued together and attached to the heat spreader using the Master Bond EP21TCHT-1 high performance epoxy. The operating temperature range for this epoxy is 4 K to 400 °F. Other common epoxies and adhesives typically used at room temperature became extremely brittle after temperature was dropped to cryogenic levels, resulting in broken contacts.

The Cu heat spreader was mounted to the cryostat cold finger using a specialized InSn 52 to 48 weight percent soft-metal-alloy (SMA) thermal interface material (TIM) to further maximize the heat transfer to the system heat sink. This material offers an outstanding thermal conductivity for large areas, exceeding any other common materials used for this purpose, such as greases or phase change materials. The finalized assembly of the package in the cryostat is shown on Fig. 6.

2.3 Temperature Control

A Cryodyne M-22, two-stage, Gifford-McMahon (G-M) cycle cryo-refrigerator operating in closed loop with a Lakeshore 805 temperature controller was used to carefully control the cryostat temperature in the range from 324 K down to 10 K. The main advantage of G-M refrigerators is that both the compressor and valve assembly can be installed away from the cool head, thus reducing both mechanical vibrations and space required for installation. These two characteristics are particularly attractive for optical applications,

Figure 6. COVEGA FPL1055C fully packaged and assembled in the cryostat.

in which both vibrations and working space clearance have to be minimized.

The performance of diode lasers is extremely sensitive to temperature, and therefore, it was of paramount importance to achieve a very stable operation temperature during characterization. A very thorough analysis of the temperature control loop was performed for this purpose. There were several important findings. First, the temperature control can be classified as a multiple-input single-output system. The temperature is affected by three heat sources: a) the heat injected from the ambient as a result of non-perfect thermal isolation, b) the cryorefrigerator heat pump cooling power and c) the heater power. Such system cannot be represented by a simple transfer function and, therefore, cannot be analyzed using conventional control theory. Second, contrary to expectations, both the proportional and integral actions of the 805 controller (a PI controller) are not proportional to temperature error in the system, but instead are proportional to the square of this error. This latter effect had a profound impact on the controller tunability. Third, the cryorefrigerator cooling capacity itself is a function of temperature, which leads to a nonlinear system.

The issues described above were addressed as follows. Heat balance analysis of two-stage, G-M cycle cryorefrigerators provided in [Thirumaleshwar 1990] suggested the load capacity of these cryorefrigerators is approximately proportional to the absolute temperature in the cool-head. A more quantitative confirmation of this observation was obtained by analyzing the experimental data provided in [Thirumaleshwar 1990] for the heat pump losses and it was confirmed that the largest heat loss contributor indeed had a nearly linear dependence on temperature. Since the ideal cooling capacity of any two-stage G-M cycle cryorefrigerator is independent of temperature [Thirumaleshwar 1986],

[Enss 2005], the expected net cooling capacity temperature dependence of typical two-stage G-M cryorefrigerators should follow the linear dependence of the losses, and therefore could be expressed as a linear function of temperature. This assumption simplified the analysis and allowed the determination of a differential equation that can approximately describe the dynamics for the whole system. Steady-state analysis of this equation under high gain conditions led to a relation useful for characterization of the cryorefrigerator given by

$$L = \frac{T_a - T_f}{\gamma} + K_s K_c (T_{sp} - T_f) \quad (1)$$

where L is defined as the heater power required to keep the cryostat temperature equal to that of the ambient when the cryorefrigerator is on, in units of W, T_a is the ambient temperature, in K, T_f is the final steady-state temperature, in K, γ is the cryorefrigerator cooling power, in units of K/W, T_{sp} is the temperature set point, in K. The parameters K_s and K_c are the sensor and (linearized) controller proportional action transfer functions in units of V/K and W/V, respectively. In this equation, γ is a function of T_f and K_c is a function of the steady-state error $\Delta T_{ss} = T_{sp} - T_f$.

Eq. (1) is an extremely useful and powerful relation for extraction of the cryorefrigerator parameters. Although it was derived under the assumption of a constant γ and linear K_c , it can be systematically used for extracting the temperature dependence of γ or the steady-state temperature error dependence of K_c . To illustrate this, first, T_{sp} can be set to $T_f + \Delta T_{ss}$, such that $T_f = T_a$. Then L can be obtained by measuring the voltage across the heater using V^2/R , where R is the heater resistance. Then, T_{sp} can be set higher and K_c can be adjusted through the controller gain setting until $T_f = T_a$ again. Under such conditions, the

first term in Eq. (1) is zero, and the second term reduces to $K_s K_c \Delta T_{ss}$, from which K_c can be found. Iterating, it is possible to construct a plot of K_c vs. ΔT_{ss} which would allow for detection of any nonlinear dependence. Then, with K_c vs. ΔT_{ss} known, T_{sp} can be set to a different temperature. After that, the system will stabilize at a temperature T_f , K_c is known for any ΔT_{ss} , and Eq. (1) can be solved for γ . Iteration would give the value of γ vs. T_f , that is, the temperature dependence of the cryorefrigerator cooling power.

Although the above procedure would lead to a full characterization of the cryorefrigerator γ and the controller K_c , for the present work the value of γ corresponding to $T_1 = 10.4$ K was taken as constant at any temperature and the exact relation for K_c was derived from electrical analysis of the controller circuit. It was found that K_c is given by

$$K_c \equiv \frac{dP_h}{d(\Delta T)} = 8 \left(\frac{R_h}{R_{eq}^2} \right) k_p^2 K_s \Delta T \quad (2)$$

where P_h is the heater power injected into the cryorefrigerator, in W, R_h is the heater Cu-Mn wire coil resistance, in Ω , k_p is the controller voltage gain setting, a dimensionless quantity, and ΔT is the instantaneous temperature error. This is how it was found that K_c is not independent of ΔT_{ss} and has a quadratic dependence on the controller gain setting k_p . In the setup, R_h was measured as 35Ω and R_{eq} was estimated as $\sim 7 \Omega$ from the controller electronic circuit analysis. Thus, when ΔT_{ss} is large, the controller transfer function would often result in saturation of the heater current and steady-state temperature oscillations in the long term. In this case, the controller tuning procedure is to start with a low gain and allow the temperature to stabilize. Then the gain has to be increased and the steady-state error should be reduced. Iteration of this procedure leads to

a very high gain value when the steady-state error is nearly zero. Simultaneously, under such conditions, the effect of the heater dominates over the other heat sources, thus leading to a simple transfer function (one input, one output) for temperature control. Thus, under very high gain conditions, the temperature steady-state error can be small and the effect of the ambient and cryorefrigerator cooling capacity can be neglected. However, if very large gains are used, any perturbations or noise in the system would lead to instability. Under such circumstances, the addition of a small integral action in the controller can be used to avoid very large gains and virtually remove the steady state error.

The suggested procedure proposed here is to be contrasted with other controller tuning procedures available in the literature [White 2002]. The procedure used here is more general in the sense that complete characterization of the cryorefrigerator can be done and the proper tuning can be designed once the information is obtained. Using the procedure proposed above, a temperature stability of better than 0.2 K was achieved over the entire temperature range.

2.4 Electrical Setup

To control the current, a Newport 8530 diode laser driver module installed on a Newport 8000 mainframe was used to sweep the laser bias current in 0.2 mA steps. From the measured short-term drift of the source, it was estimated that the precision for the current was $\sim 105 \mu\text{A}$ at 100 mA, but it decreased to $\sim 78 \mu\text{A}$ at 10 mA or less. Thus a significant uncertainty was expected if minimum steps were used. Indeed, calculation of derivatives

was affected by these imprecisions. These effects were removed by averaging with neighboring measurement points before the estimations of the derivatives.

A Keithley 2000 high-precision multimeter was used to independently measure the terminal voltage for the diode laser, using dedicated sensing wires. The instrument provided an outstanding accuracy of 35 μV at voltages lower than 1 V DC, according to the manufacturer's specification. However, the observed short-term voltage accuracy was $\sim 6 \mu\text{V}$, thus giving an overall accuracy of $\sim 41 \mu\text{V}$.

2.5 Optical Setup

2.5.1 Collimation

Temperature characterization required the diode laser to be placed inside the cryostat, where limited access to the light emitted precluded absolute measurements of the total optical power output. Instead, free-space optics was used to properly collimate and guide the beam to the optical power meter and spectrometer for $L-I$ and spectral characterization, respectively. Since the laser output beam for most semiconductor lasers is strongly divergent, an aspherical lens was used for collimation in an attempt to reduce further power losses due to aberrations.

The positioning of the laser in the cryostat prevented collection of light close to the source, where the beam size can be easily handled with standard optics. The plane of light emission was estimated to be ~ 5 cm into the cryostat, as seen from the output windows. Since the windows on the cryostat have ~ 4 cm diameter, the maximum half angle of emission of light out of the cryostat was approximately $\alpha_i = \tan^{-1}[(4/2)/5] = 0.381 \text{ rad} = 21.8^\circ$. Thus, at a distance of 7.5 cm, where there is room to place the first

optical element, the beam size was already $\sim 2 \times 7.5 \times \tan(21.8^\circ) \cong 6$ cm. Thus, the first optical element in the system should be at least this wide and have enough focusing power to either collimate or refocus the strongly diverging laser beam, and do it with the least possible aberration. An aspherical lens with acceptable characteristics was available in the laboratory. This lens was $\sim 2.5''$ or ~ 6.30 cm in diameter, had a focus of ~ 6 cm, and was corrected for spherical aberrations. Fig. 7 shows a picture of this lens, for which no identification was available.

Figure 7. Aspherical lens used for collimation of laser beam.

The aspherical lens was mounted on an adjustable stage and was positioned to collimate the beam as much as possible, as measured from the far-field divergence angle associated with the beam spot. Contrary to expectations, substantial optical losses were observed at this position. These losses were caused by strongly diverging beams superimposed on the overall collimated beam. In order to avoid these losses, the position of the lens was adjusted to align those multiple beams and increase the beam intensity, but at the expense

of degrading the overall beam collimation, which exhibited an appreciable divergence angle. Thus, the beam had to be slightly de-collimated, up to the point where the power measured at the detector after the next optical stage was maximized. Once this was done, the laser output was characterized. It was found that the far field divergence angle θ_{FF} was $\cong 0.0136 \text{ rad} = 0.754^\circ$. Such estimation was done by measuring the beam spot size at a distance of $\sim 122 \text{ cm}$ and $\sim 350 \text{ cm}$ away from the lens, for which the beam radius was $\sim 2.5 \text{ cm}$ and $\sim 5.5 \text{ cm}$, respectively. Then, the temperature was dropped to 10 K and it was observed that the beam divergence was nearly unaffected. This geometrical argument was used to conclude that the effect of collimation at the first lens was nearly negligible as the temperature of the laser was dropped. Thus, any measured power variations should only arise mostly from variations of the actual beam intensity.

A more careful analysis would require consideration of laser emission diffraction effects, which are dependent on the emission wavelength. This was found to change with temperature by approximately 100 nm over the whole temperature range. Diffraction would cause a decrease in the laser emission angle as the wavelength is reduced, and should consequently increase somewhat the photon flux across the fixed area of the cryostat window. However, diffraction should not affect the external emission angle, since this angle is determined by a spatial filter provided by the cryostat window diameter and the distance to the laser facet, as calculated before. This would explain why the collimated beam divergence was not changing with temperature. Diffraction effects were not considered in this work, but it is clear that a more advanced setup would require the addition of a pupil before the collimating lens that could be adjusted to compensate for these variations as to maintain a constant photon flux density at all temperatures. These

variations would have to be quantified from the strict far-field theory of laser beam emissions [Zeng 1993], although simplified models are also available [Naqwi 1990].

As a conclusion of this discussion, it is clear that a substantial amount of power was lost in the optical setup and the optical power collection efficiency η_{col} was reduced to some extent, although it was estimated that such losses were not strongly affected by temperature variations.

2.5.2 Beam Alignment

It was necessary to provide a beam alignment section to spatially couple the collimated laser beam into the optical matching stage. This was achieved by using a typical two mirror configuration. Although this method is considered common knowledge, details of the actual alignment procedure are often misunderstood. A mathematical model is presented here, aiming to facilitate the alignment and clarify the underlying, and often overlooked, assumptions.

Figure 8. Equivalent optical system for the beam alignment section.

The model was developed using ray matrix methods in paraxial optics approximation. By using the method of virtual images, it was possible to effectively represent the optical alignment setup. Fig. 8 represents such optical alignment section, where an arbitrary ray at height y_0 enters the subsystem at an angle α_0 with respect to the optical axis. The aim is to produce a ray exiting the system at the other side at y_f with an angle α_f , using only two mirrors.

In the proposed model, the input plane is located at a distance l_1 away from the first mirror, l_2 is defined as the distance between the mirrors, and l_3 is the distance between the second mirror and the exit plane. The system can be described by five matrices, representing three translations and two reflections, as follows

$$\begin{bmatrix} y_f \\ \alpha_f \end{bmatrix} = \begin{bmatrix} 1 & l_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & k_2 \end{bmatrix} \begin{bmatrix} 1 & l_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & k_1 \end{bmatrix} \begin{bmatrix} 1 & l_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} y_0 \\ \alpha_0 \end{bmatrix} \quad (3)$$

In the above, the matrices containing the k factors define the reflection of the mirrors, where the resulting angle is given by $k_n\alpha_i$, with α_i being the incidence angle with respect to the optical axis. The change in direction of the beam upon reflection from the mirrors is not represented in the method. This is not necessary, since matrix methods only describe rays by specifying their vertical position and angle with respect to the optical axis. The following expression can be obtained by performing the matrix multiplication,

$$\begin{bmatrix} y_f \\ \alpha_f \end{bmatrix} = \begin{bmatrix} 1 & l_1 + l_2k_2 + l_3k_1k_2 \\ 0 & k_1k_2 \end{bmatrix} \begin{bmatrix} y_0 \\ \alpha_0 \end{bmatrix} \quad (4)$$

The above matrix equation defines a system of two equations, given by

$$y_f = y_0 + (l_1 + l_2k_2 + l_3k_1k_2)\alpha_0 \quad (5)$$

$$\alpha_f = k_1k_2\alpha_0 \quad (6)$$

Hence, the emerging beam location can be specified by the coordinates $(l_1 + l_2 + l_3, y_f)$ with the angle $k_1k_2\alpha_0$ defined with respect to the optical axis. The resulting equations demonstrate that modification of either k_1 or k_2 by tilting the mirrors will lead to simultaneous changes in both y_f and α_f , a condition that would severely limit the use of the system for beam alignment. It is also clear that adjusting any of the distances l_1 , l_2 , or l_3 , will only affect y_f , as required for beam alignment. However, this option implies all the following optical sections would have to be relocated as well, a very inconvenient consequence. Thus, it was desirable to modify the system to keep the sum of all distances constant, while allowing alignment by only tilting the mirrors. From the above relations,

it can be seen that this restriction can be met by setting $l_3 = 0$, thus reducing the equations to

$$y_f = y_0 + (l_1 + l_2 k_1) \alpha_0 \quad (7)$$

$$\alpha_f = k_1 k_2 \alpha_0 \quad (8)$$

where it is clear that adjusting the second mirror tilt will exclusively affect y_f and adjusting the first mirror will only affect α_f . Thus, the alignment procedure for beam alignment using two mirrors should be:

1. Position the second mirror at the entrance plane of the following optical section.
2. Modify k_1 by tilting the first mirror to set y_f , the exit vertical position.
3. Modify k_2 by tilting the second mirror to tune α_f , the exit angle.

This procedure was successfully used in our setup for aligning the beam into the next optical stage for optical matching to the spectrometer and focusing of the beam into the detector window. It was repeatedly used every time the temperature was changed to compensate for the beam emission direction and position changes due to cryostat thermal contraction/dilation effects.

2.5.3 Optical Matching

As previously stated, it was necessary to optically match the input of the monochromator to minimize the signal power necessary to perform the spectral measurements. The optical matching is determined by the f/# number for the instrument, which is a measure of the acceptance angle for the input light at the focal plane. For the CVI DK480 monochromator used in this experiment, this focal plane is at the entrance slit. Since the specified f/# for this instrument is 7.8, the maximum angle of incidence for the extreme

Figure 9. Definition of the optical problem for $f/\#$ matching to the monochromator.

rays is simply $\tan^{-1}[1/(2 \times 7.8)] = 0.064 \text{ rad} = 3.67^\circ$. Thus, optical matching to the monochromator required optics to image the laser output facet at the monochromator entrance slit with the extreme rays roughly defined by the beam FWHM points entering at this angle.

The matching problem for this experimental setup is depicted in Fig. 9. As stated before, it was not possible to perfectly collimate the laser output beam and, therefore, the extreme rays associated with the input laser beam will travel at a certain angle α_i with respect to the optical axis of the system. For a wide beam, they can also appear at a distance y_i from the optical axis. The system has to transform this beam in such a way that extreme rays leave the system at an angle $\alpha_o = \pm 3.67^\circ$ with respect to the optical axis at a suitable distance y_o to focus the beam at the monochromator input. The resulting output image can be inverted. In addition, the system would have to produce such

transformation using only positive lenses, as these were the only type available in the laboratory.

A simplified matrix method using paraxial optics was used to solve the matching problem. The intent was to quickly assess several possible configurations of lenses having different $f/\#$. Thin-lens approximation was used. In the method, incoming and exiting rays are represented by vectors $\mathbf{v}_i$ and $\mathbf{v}_o$ defined as [Pedrotti 2007]

$$\mathbf{v}_i = \begin{bmatrix} y_i \\ \alpha_i \end{bmatrix} \quad (9)$$

$$\mathbf{v}_o = \begin{bmatrix} y_o \\ \alpha_o \end{bmatrix} \quad (10)$$

Propagation in free space is defined by a translation matrix, given by

$$\mathbf{T}_n = \begin{bmatrix} 1 & d_n \\ 0 & 1 \end{bmatrix} \quad n = 0, 1, \dots, N \quad (11)$$

where d_n is the translation distance between the entrance plane and the first lens (when $n = 0$), between the lenses, or between the last lense and the exit plane, and N is the total number of lenses. Similarly, a thin lens is represented by the matrix

$$\mathbf{L}_n = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_n} & 1 \end{bmatrix} \quad n = 1, \dots, N \quad (12)$$

where f_n is the lens focal length, a positive or negative quantity for convex and concave lenses, respectively. An arbitrary optical system is now represented by multiplying each element matrix in reverse order, i.e. as seen from the input. Thus, the input and output

vector relation for a system of N lenses arranged along the sample optical axis can now be written as

$$\mathbf{v}_o = \left(\prod_{n=N}^1 \mathbf{T}_n \mathbf{L}_n \right) \mathbf{T}_0 \mathbf{v}_i \quad (13)$$

Per the above definition, the first matrix $\mathbf{T}_0$ in the system is always a transport matrix that represents the distance from the entrance plane to the first lens. Since the distance between any two lenses and passing the last lens can take any value, the resulting optical system can have an arbitrary total length. Mathematically, the system will also have an arbitrary number of solutions. Thus, it is convenient to add an additional equation to the system to impose a total length restriction. The relation is given by

$$L = \sum_{n=0}^N d_n \quad (14)$$

In the method proposed above, the finite size of the optics involved had been ignored. It is impossible to incorporate this restriction in the model, since the paraxial optics approach has ignored this consideration from the very beginning. Thus, a complete version of the model would require the theory of ray tracing for meridional rays. This was beyond the scope of the present work. However, it is clear that having a very large beam spot at the system input may restrict the implementable solutions obtained from the simplified model.

A MATLAB program was written to implement the above relations and quickly assess possible combinations of available lenses. It was found that two lenses with focal lengths of 10 and 5 cm would produce the required matching when $\alpha_i = 0.754^\circ$, which was the nearly collimated laser beam divergence angle, $y_i = 3.5/2$ cm, the half beam width after collimation, $\alpha_o = 3.67^\circ$, as required by the monochromator, and $y_o = 0$ cm, which implies the exit plane of the system would be the same as the monochromator entrance slit plane. Fig. 10 shows the plot for the distances, in cm, for these lenses as a function of the system total length, in inches. From the plot, it is important to note that the quantity d_1 remained roughly constant across the whole total length solution range. This was consistent with the fact that the focusing power of a two-lens system is strongly dependent on this distance only, and nearly independent of the input and output translations.

The most important conclusion from this analysis was that, for the variety of lenses available in the laboratory, a long space was required to achieve the matching. For the

Figure 10. Optical matching results for a system of two positive lenses.

two lenses considered, matching was possible only when the total system distance was larger than 30 in, at a minimum. Other combinations of lenses required even longer distances and thus were discarded.

2.5.4 Detection

An Agilent 8153B optical power meter was used for measuring the optical power. Under regular operating conditions, it was observed that the optical power sensitivity of the detector was on the order of a few nanowatts around 1.55 μm , which was sufficient to record typical optical output power levels for currents above 1 mA injected to the FPL1055C laser. For each temperature, the meter was set to the central wavelength of laser emission corresponding to a current of 100 mA before a complete L - I sweep was performed.

2.6 Spectral Measurements

2.6.1 Monochromator

The laser spectra were measured with the CVI DK480 Czerny-Turner type monochromator equipped with a 600 grooves/mm, 68×68 mm, 3.2 nm/mm dispersion grating. The monochromator was used at a constant slit width of 50 μm at all wavelengths. The diffraction limit of resolution for the grating is given by [Pedrotti 2007]

$$\Delta\lambda = \frac{\lambda}{mdW} \quad (15)$$

where λ is the wavelength, m is the order of diffraction, d is the groove density, in mm^{-1} , and W is the grating width, in mm. From the above, the diffraction resolution limit for the monochromator would be $1.55 \mu\text{m}/(1 \times 600 \text{ mm}^{-1} \times 68 \text{ mm}) = 0.038 \text{ nm}$. However, this

type of monochromator is not limited by the grating diffraction only, but also by the entrance slit width, according to the relation [Radziemski 1981]

$$\frac{\Delta\lambda}{\Delta x} = \frac{a \cos(\theta_m)}{mf} \quad (16)$$

where $\Delta\lambda/\Delta x$ is the dispersion in units of nm/mm of entrance slit, also known as plate factor, a is the groove separation, in nm, θ_m is the angle the grating is rotated as measured from the point at which white light is specularly reflected through the instrument and f is the mirror focal length, in mm. In turn, for the angle θ_m can be determined from the relation [Murty 1974]

$$\lambda = \frac{(2 \cos \phi) \sin \theta_m}{md} \quad (17)$$

where λ is the wavelength appearing at the exit slit of the Czerny-Turner monochromator, ϕ is the Ebert angle, determined by the position of the grating, the collimating mirror and the focusing mirror; and is constant for a particular instrument, while m , θ_m and d are the same as before. For the DK480, $\phi = 18^\circ$ [CVI 1998]. Thus, taking $\lambda = 1.55 \mu\text{m}$, $m = 1$, and $d = 600$ grooves/mm, Eq. (17) gives 29.27° for θ_m . Inserting this angle into Eq. (16) with $a = 1/d$, in nm units, and $f = 480$ mm [CVI 1998], the instrument dispersion is 3.029 nm/mm. Since the slit width was fixed to $50 \mu\text{m}$, the resolution is approximately $3.029 \text{ nm/mm} \times 0.050 \text{ mm} = 0.151 \text{ nm}$, under the assumption that $f/\#$ matching is in place and the grating has been completely illuminated. Care was taken to meet these conditions, as outlined in previous sections.

It is obvious from Eq. (17) that θ_m has a wavelength dependence. In turn, this affects the resolution, as Eq. (16) indicates. However, it is possible to control Δx in Eq. (16) in order to keep the resolution constant for large changes in λ . This mode of operation is called constant spectral resolution (CSR). This feature was not implemented during experiments as the wavelength variation was rather small. At low temperatures, when $\lambda \sim 1.4 \mu\text{m}$, $\theta_m = 26.20^\circ$ and the dispersion per unit length of exit slit per Eq. (16) is 3.12 nm/mm. Thus, compared to 0.151 nm at 1.55 μm , the resolution in this case was $3.12 \text{ nm/mm} \times 0.050 \text{ mm} = 0.156 \text{ nm}$, which is a small variation in comparison with the typical $\sim 0.3 \text{ nm}$ linewidths observed for the FPL1055C emission modes.

2.6.2 Signal Amplification

A Stanford Research Systems (SRS) SR850 Digital Signal Processor (DSP) Lock-in Amplifier was used to recover the weak optical signal emerging from the monochromator. As stated before, in addition to the inherent power loss associated with the spectrometer operation (narrow bandwidth), it was necessary to minimize the fraction of power guided to the monochromator at the beam splitter to let most of it be directed to the power sensor. This was important because the measured optical power would be used to estimate the laser external quantum efficiency. Yet the optical signal directed to the monochromator would have to be strong enough to provide accurate information on the laser modes and, in as much as possible, to retain weak spectral features. The degree to which both of these requirements could be addressed simultaneously depended on how well the lock-in amplification technique was implemented.

The theory of operation of lock-in amplifiers is very well explained in the instrument manual [SRS 1992]. Nonetheless, the implementation of the laser spectral measurements

required careful selection of the instrument settings to produce highly accurate and error-free results. The procedure followed to determine the settings of the relevant parameters is presented in the next few sections.

2.6.2.1 Signal Detection

Light exiting the monochromator induces a photocurrent in the New Focus 2153 photoreceiver used in this experiment. The photoreceiver is a 1 mm diameter InGaAs photodetector in a PIN configuration that can detect light in the range from 800 to 1700 nm. Although the generated photocurrent can be extremely weak for the spectral measurements, the 2153 photoreceiver pre-amplifies and converts the photocurrent to an equivalent voltage signal before passing it to the output coupling circuitry. The detector has three couple modes: a) DC (low gain), b) low (gain) AC and c) high (gain) AC. The low AC mode was used for characterization of the FPL1055C. In this mode the amplification and output coupling circuits have an overall gain of $\sim 2 \times 10^{10}$ V/A and a 3 dB bandwidth of ~ 750 Hz. It was observed that a higher gain setting would saturate both the detector and the lock-in amplifier when the FPL1055C was biased at high currents. On the other hand, the DC setting was discarded in an attempt to minimize the low-frequency noise that may be coupled into the lock-in amplifier input. This finding was important and the following sections discuss how this was verified.

Nonetheless, even in the AC mode, the detector amplification process not only boosts the signal, but also increases the intrinsic noise of the detector. This noise is broadband in nature. If this noise is not filtered properly, it could exceed the power in the signal itself. The power of the lock-in amplification technique relies in the ability to extract the signal even in the presence of high noise power density. One can think of a lock-in amplifier as

a very high gain amplifier operating with an input band-pass filter of extremely narrow bandwidth centered exactly at the frequency of the extracted signal. Under such conditions, the actual noise power reaching the amplifier input is oftentimes negligible compared with that of the signal power. The determination of the important lock-in amplifier settings is discussed next.

2.6.2.2 Gain

In the SR850 DSP Lock-in Amplifier, the overall amplifier gain (AC plus DC) is determined by the sensitivity parameter. The exact relation between the gain parameter and sensitivity was not provided in [SRS 1992]. The lock-in amplifier allows the input signal to be amplified in voltage or current mode. Since the detector signal was provided in volts, the measurements were done in input voltage mode. Using this mode, it was observed that for a sensitivity of 1 V full scale (FS), the overall amplifier gain was only 20 dB, whereas for the minimum sensitivity value of 2 nV FS, the gain was 194 dB. Both settings result in a maximum value of 10 V for R , the lock-in amplifier output voltage.

For laser spectral measurements, it was required to characterize the laser spectrum at different values of injection current. Therefore, it was necessary to set the sensitivity to a level such that the spectra under the highest injection current conditions would not saturate the lock-in amplifier, when configured with the selected settings. The optical alignment was also very important because, to find the right sensitivity, it was necessary to re-align the system prior to measuring to achieve maximum power. Taking into account these aspects for the setup in place, it was found that a sensitivity of ~ 20 mV was suitable for FPL1055C characterization in the experimental setup at a maximum injection current of 400 mA after the optical setup has been aligned for maximum power.

2.6.2.3 Low Pass Filter Time Constant

The purpose of the low-pass filter (LPF) in a lock-in amplifier is two-fold. From the noise management perspective, it controls the equivalent noise band width (ENBW) given by $1/(4T)$, in units of Hz, where T is the filter time constant. In an analog LPF, T would be given by the RC product of the filter resistance and capacitance, respectively. In the SR850, this filter is digital (implemented as numerical operations in a digital signal processor), so this interpretation is meaningless. However, in both cases T is related to the filter cut-off frequency through the relation $T = 1/(2\pi f_c)$. Since the LPF rejects all noise outside the ENBW, a high value of T implies a low ENBW and thus less transmitted noise to the DC amplifier (see details in [SRS 1992]). These are the DC offset errors. From the user perspective, the LPF can be used to remove undesired drift present in the measurements, occurring over a certain period. In this work, the main source of drift was originated by the temperature stability of the cryorefrigerator. It was found that the temperature drift period was ~ 5 min. Therefore, for complete elimination of this periodic drift error, T would have to be set to a few periods of the drift oscillations. This was clearly not practical. Thus, the determination of T was more concerned with the experiment duration time. A reasonable value for T was 1 s, such that each measurement would take ~ 3 s per data point. Fortunately, the DC offset error for this rather short time was not significant, as it was experimentally determined that the noise in the system was dominated by the SR850 ADC noise for the chosen gain and dynamic reserve ranges required for the measurements (see the dynamic noise reserve section).

As a consequence of the impossibility of eliminating the DC drift errors due to the temperature instabilities, sometimes it was necessary to perform a second sweep of the

laser spectrum near the expected maximum, when the center wavelength could not be clearly identified the first time. This second sweep would be performed using $T = 1$ ks, to accurately estimate the highest power mode.

2.6.2.4 Dynamic Noise Reserve

The distribution of the gain (AC versus DC) is set by the dynamic reserve setting (see [SRS 1992] for a detailed explanation of the amplifier gain stages). In the SR850, the AC gain is provided by the ADC low noise amplifier (LNA) with a voltage linear gain ranging from 7 to 1000. As for the digital DC amplifier, the gain is probably adjusted as to provide the overall gain reported on the screen. Regardless of the actual definition, it is clear that, for a given total gain, part of it goes to the analog LNA and part of it to the digital DC amplifier.

It was found that a high dynamic reserve setting, in units of dB, implies that most of the gain goes to the digital DC amplifier, while for a low dynamic reserve setting, most of the gain goes to the analog LNA. Thus, if the input signal is noisy, a maximum reserve may be necessary to remove as much gain as possible from the unfiltered LNA. If a high gain is used there, amplification of noise may result in DC offset errors or power overloading at some point in the system. On the other hand, if the input noise is small, then it is convenient to set the reserve to a minimum in order to maximize the gain on the AC amplifier and improve the input signal to noise ratio.

Considering the above remarks, a simple experiment was performed to determine the source of noise dominating the measurements. The cryogenic system was turned on and stabilized at 299.9 K. The laser was turned on and the injection current was set to 200

mA. Then, the optical system was aligned and spectral measurements were performed to identify the exact wavelength of one lasing mode. After this, the monochromator was set to the wavelength found for this mode (1554 nm). The photoreceiver was set to low AC gain, as it was determined the high setting would saturate the lock-in amplifier. Since the temperature drift period for the laser was estimated to be ~ 5 min, the LPF T was set to 1 ks to minimize drift errors present in the system. The sensitivity (gain) was then set to a typical high value, such as 100 nA (40 dB gain). The reserve was initially set to minimum, in this case 0 dB, implying LNA gain was 40 dB and digital DC amplifier gain was 0 dB. After waiting for more than 20 minutes, it was found that $R = 14.93$ mV. Then the reserve was changed to maximum, in this case 40 dB, implying LNA gain as 0 dB and digital DC amplifier gain was 40 dB. After waiting for more than 20 min, it was found that $R = 16.69$ mV. Thus, R increased when the LNA amplifier gain was reduced. This can only be explained by noise generated internally at the lock-in amplifier ADC.

A second experiment was run at a different sensitivity level in order to confirm the above conclusion. Under the same conditions, the sensitivity was set to 20 mV (gain 54 dB). Then, the reserve was set to a minimum, in this case 4 dB, implying LNA gain was 50 dB, and digital DC amplifier gain was 4 dB. After waiting for more than 20 min, R was found to be 18.656 mV. Then, the reserve was set to maximum, 34 dB in this case, implying LNA gain was 20 dB and digital DC amplifier gain was 34 dB. After waiting for more than 20 minutes, it was found that $R = 19.801$ mV. Thus, once again, R increased when the LNA gain was reduced, indicating that the DC offset error could indeed be attributed to ADC noise.

In this way, it was concluded that the internal lock-in amplifier ADC noise dominates the measurement when the photoreceiver was used in the AC low mode, and therefore, the reserve should be set to MAX for typical laser spectral measurements in this setup. The effect of further reducing the LPF time constant to accelerate the experiments was not explored, since temperature DC drift errors would be increased in this case. However, in principle, the experiments described above could be repeated with lower values of T in order to find the fastest time at which the errors from the photoreceiver would dominate.

2.6.2.5 Reference Signal

As stated before, the use of the lock-in amplifier technique required a reference sinusoidal signal in phase with the modulated input signal. In the case of lasers, this modulation can be implemented either electrically or optically. The former technique requires an electrical modulator that can supply an AC signal superimposed on the DC current feeding the laser. This AC signal can have a very low frequency, typically less than a few kHz, to ensure the modulation does not compete with any dynamic process in the device. Alternatively, optical techniques do not disturb the device in any way. Instead, the output beam is modulated using an optical chopper. These devices work as cyclic shutters that cut the beam at a specified frequency, while also generating a reference optical signal locked to the shutting frequency using independent optical encoders sampling the shutter frequency.

As explained in the instrument manual (see [SRS 1992]), the lock-in amplifier technique relies on the ability of the phase-locked loop (PLL) circuitry to lock the internal local oscillator (LO) to a reference signal. Any jitter present in this signal reduces the ability of the amplifier to generate the expected output signal. Thus, it was important to evaluate

which of the modulation options could offer the best performance. It was found that the best reference signal available was provided by the lock-in amplifier itself. The SR850 synthesizes an extremely stable signal with very high spectral purity aimed for direct modulation of devices. Early experiments, not reported in this thesis, relied on this capability to electrically modulate the laser. The reason was that, early versions of the experimental setup did not consider the optical matching to the monochromator and, as a result, the signal detected during spectral measurements was extremely weak, very close to the noise level of the photoreceiver, thus requiring very accurate phase locking for signal amplification.

However, after the introduction of the optical matching stage to the monochromator described in Section 2.5.3, the superior electrical technique was no longer necessary and the more conventional optical technique was implemented to prevent any possible indirect effects on the laser performance.

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CHAPTER 3. METHODS FOR EXTRACTION OF LASER PARAMETERS

In this chapter, the most important laser operating parameters are presented and basic procedures for determining them from the L - I and I - V characteristics are discussed.

3.1 External Quantum Efficiency (η_d)

The external quantum efficiency is a measure of how well injected current is converted to useful optical output once the lasing threshold has been reached. For an ideal laser, all current injected is transformed into photons and all these photons can survive their travel through optical cavity to become part of the useful optical output. Under such conditions, q coulombs of charge per second generate hc/λ_0 joules per second and the corresponding L - I curve would have a slope given by $(hc/\lambda_0)/q = hc/q\lambda_0$ in units of W/A. In contrast, in a real device not all the injected current provides useful carriers in the active region, and the generated photons can be lost within the cavity before they can contribute to the optical output. In this case, the L - I relation can be measured directly from the change of the optical output power in response to a change in the injected current, that is, from the ratio $\Delta P/\Delta I$. When comparing the real laser performance against the ideal device, the ratio $(\Delta P/\Delta I)/(hc/q\lambda_0) = (\Delta P/\Delta I)(q\lambda_0/hc)$, a normalized parameter, is a measure of how well the injected current is converted to useful optical output. This parameter is called *external quantum efficiency* or simply *differential efficiency*, and is given by [Coldren 2012]

$$\eta_d = \left(\frac{q\lambda_0}{hc} \right) \frac{\Delta P}{\Delta I}, \quad I > I_{th} \quad (18)$$

where I_{th} is the threshold current.

A high differential efficiency is always desired, since it means less current has to be injected to achieve the same optical output power.

3.2 Transparency Current (I_{tr}) and Threshold Current (I_{th})

Electroluminescence in semiconductor lasers is conventionally explained through two coupled rate equations to model the interaction in time between semiconductor carrier recombination processes and emission of photons into an optical mode. The two fundamental equations for can this process can be written as [Coldren 2012]

$$dN/dt = R_{inj} - (R_{sp} + R_{nr}) - R_{st} \quad (19)$$

$$dS/dt = \Gamma(R_{st} + \beta R_{sp}) - \gamma_c S \quad (20)$$

where N and S are the volumetric carrier and photon densities, respectively, R_{inj} is the volumetric carrier injection rate *into the active region*, R_{sp} , R_{nr} , and R_{st} are the volumetric spontaneous (radiative), nonradiative, and stimulated emission carrier recombination rates *in the active region*, respectively, Γ is the confinement factor, βR_{sp} is the fraction of the spontaneous emission radiation injected into the optical lasing mode, and γ_c is the photon cavity decay rate as a result of external emission. The laser modal optical output is given by [Coldren 2012]

$$P_{out} = \eta_{col} \gamma_{out} (hc/\lambda) V_S S \quad (21)$$

where η_{col} is an output collection efficiency factor, γ_{out} is the photon output rate, λ is the optical output mode wavelength, and V_s is the volume occupied by the mode in the optical cavity. Setting $dN/dt = 0$ and $dS/dt = 0$ and solving Eq. (20) for S , it can be shown that

$$P_{out} = \eta_{col} (\gamma_{out} / \gamma_c) (hc / \lambda) (V) [(R_{inj} + \beta R_{sp}) - (R_{sp} + R_{nr})] \quad (22)$$

where V is the active region volume, equal to ΓV_s . In this form, the effect of stimulated emission is accounted by R_{inj} , which can be now treated as an independent term determined by the injection current, imposing a functional dependence for β , R_{sp} and R_{nr} . Eq. (22) clearly shows that the laser optical output is the result of the competing effects of carrier injection and spontaneous and nonradiative recombination, with a small portion of the spontaneous emission injecting photons into the optical mode. Substituting $R_{inj} = \eta_{inj} I / qV$ and using Eq. (19) in Eq. (22), the output power can be rewritten as

$$P_{out} = \eta_{col} \eta_d (\eta_r \beta) \left[\frac{1 + \beta R_{sp} / R_{st}}{(\eta_r \beta) + \beta R_{sp} / R_{st}} \right] \left(\frac{hc}{q\lambda} \right) I \quad (23)$$

where $\eta_r = R_{sp} / (R_{sp} + R_{nr})$, the internal efficiency, and $\eta_d = \eta_{inj} (\gamma_{out} / \gamma_c)$, the external differential efficiency, have been used. In these expressions, η_{inj} is the injection efficiency that represents the fraction of current that results in carriers injected into the active region where recombination takes place, including both radiative and nonradiative components. It is clear from Eq. (23) that when R_{st} dominates, the output power reduces to

$$P_{out} = \eta_{col} \eta_d \left(\frac{hc}{q\lambda} \right) I \quad (24)$$

which is valid only when $I > I_{th}$. A correction to Eq. (24) is necessary to account for near-threshold behavior, leading to the well-known above-threshold approximation [Coldren 2012]:

$$P_{out} = \eta_{col} \eta_d \left(\frac{hc}{q\lambda} \right) (I - I_{th}), \quad I > I_{th} \quad (25)$$

Eq. (25) states that the measurable optical output power is a function of the fraction of the current exceeding the threshold current. This regime describes the device operation when stimulated emission dominates. Alternatively, near transparency as $R_{st} \rightarrow 0$, the output power is reduced to $P_{out} = (\beta\eta_r)[\eta_{col}\eta_d(hc/q\lambda)]I$, which correctly indicates that the optical output is just the fraction of spontaneous emission coupled into the mode. The region $R_{st} > 0$ spans the sub-threshold, threshold, and lasing regimes. Intuitively, it is expected that P_{out} would increase super-linearly in the sub-threshold region as some stimulated emission readily contributes to the optical mode buildup up to a point where optical losses are nearly overcome, which defines the transition to the threshold region. Similarly, below transparency, some additional losses should occur owing to active region absorption, which implies the output power should decrease sub-linearly. These observations suggest that calculation of the second derivative of the L - I characteristic under threshold should give a local minimum corresponding to transparency, in addition to the well-known absolute maximum corresponding to threshold. The experimental measurements reported in this thesis confirmed the existence of such minimum. Thus, by measuring the slope of the L - I curve above threshold, it is possible to estimate η_d , while by measuring the slope in the vicinity of the transparency current, it is possible to

estimate the product $\eta_i\beta$ at transparency, although determination of this latter quantity has not been attempted in the present work.

3.3 Electrical Characteristics

A simple electrical model proposed by Barnes and Paoli [Barnes 1976] was used for electrical characterization. In the model, the semiconductor laser is represented by an ideal diode with an ideality factor parameter n , a series resistance R , and a shunt resistance R_{sh} , as depicted on Fig. 11. For this circuit, the voltage and current relation are given by the transcendental equation [Barnes 1976]

$$I = V/R_{sh} + I_0 \left[\exp \left[\frac{(1 + R/R_{sh})V - IR}{aV_T} \right] - 1 \right] \quad (26)$$

where V is the diode terminal voltage, I_0 is the diode reverse saturation current, a is the ideality factor, and V_T is the “thermal voltage” defined as $V_T = kT/q$. The model is valid for current values below threshold. Above threshold, the diode voltage is nearly saturated at its threshold value V_{sat} and the diode current is nearly independent of the voltage.

Rearranging Eq. (26) to find an expression for V and differentiating with respect to I , it

Figure 11. Simple electrical circuit model for electrical laser characterization.

can be shown that

$$dV/dI = \left[R + \frac{aV_T}{I(1 + I_0/I) - V/R_{sh}} \right] / \left[\left(1 + \frac{R}{R_{sh}} \right) + \frac{aV_T}{R_{sh}} \left[\frac{1}{I(1 + I_0/I) - V/R_{sh}} \right] \right] \quad (27)$$

which is the same as the result reported by Barnes and Paoli [Barnes 1976], but written in a slightly different form. Since I_0/I is typically much less than 1, and for well-behaved lasers with large R_{sh} operating at currents immediately below threshold $R/R_{sh} \ll 1$, $V/R_{sh} \ll I_{th}$ and $aV_T/I \ll R_{sh}$, with $V \approx V_{sat}$, Eq. (27) reduces to the usual expression $R + aV_T/I$. Therefore, the slope in a plot of dV/dI vs. $1/I$ yields the value of V_T , while R is given by the y-intercept. Alternatively, above threshold, V saturates at V_{sat} , and R is simply equal to dV/dI . Thus, it is possible to estimate R by taking the derivative of the voltage with respect to current both below and above threshold. However, the above assumptions may no longer hold at low temperatures, because I_{th} can dramatically decrease while V_{sat} increases and R can be much larger [Katz 1985], such that R/R_{sh} may not be much less than unity. Nonetheless, it is always possible to evaluate Eq. (27) at a sufficiently high current such that $V_{sat}/R_{sh} \ll I$ and $aV_T/I \ll R_{sh}$ are satisfied, leading to

$$r_s \equiv dV/dI = R/(1 + R/R_{sh}) \quad (28)$$

where r_s is the device series resistance observed on the terminal, and the derivative must be evaluated at a current level sufficiently high, such that dV/dI is nearly constant or $d^2V/dI^2 \approx 0$. From Eq. (28), it is clear that $r_s = R$ only if $R/R_{sh} \ll 1$, an often overlooked consideration. Solving for R from Eq. (28) and plugging it into Eq. (26), the final form suitable for fitting to experimental data is

$$I = V/R_{sh} + I_0 \left[\exp \left[\frac{V - Ir_s}{aV_T(1 - r_s/R_{sh})} \right] - 1 \right], I \leq I_{th} \quad (29)$$

Chapter References

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CHAPTER 4. EXPERIMENTAL RESULTS

Figure 12. Linear plots of $L-I$ characteristic from 320 K down to 10 K.

Figure 13. Semi-log plots of $I-V$ characteristics from 15 K up to 300 K.

Figure 14. Sub-threshold L - I characteristic differential analysis at (a) 300 K, (b) 240 K, (c) 120 K and (d) 10 K.

Figs. 12 and 13 depict the measured L - I and V - I characteristics for the FPL1055C laser.

The scaling and ranges used in these figures have been chosen to facilitate the analysis process presented next. These figures comprise the full set of data used for the extraction of the laser parameters. As outlined in Chapter 3, it was necessary to employ rigorous and systematic extraction methods in order to reliably analyze their temperature dependence. This extraction process and the results are discussed in the next few sections.

4.1 Threshold and Transparency Currents

Fig. 14 shows the log-log plots of the L - I characteristics along with the second derivative d^2P/dI^2 for selected temperatures. The bias current was changed in 0.2 mA steps to ensure the sensitivity required to estimate the derivatives reliably. The uncertainty in the measurements arising from temperature and bias current variations was reduced by smoothing the optical power response by averaging the values in a window of $\sim 1 - 2$ mA until a continuous curve spanning the sub-threshold and threshold regions was obtained.

The time between measurements was set to > 3 s to attenuate the effect of the short-term drift error in the system, while keeping the experiment duration within a reasonable limit. The plots clearly indicate the effectiveness of the method is reduced at lower temperatures, where the second derivative minimum is harder to determine. Despite all these experimental limitations, a fairly well-defined second derivative minimum could be detected down to 50 K (not shown). Below this temperature, the current resolution was insufficient to reliably detect the expected minimum, as can be seen in Fig. 14d at the lowest temperature of 10 K. The laser threshold current was also estimated from these plots by finding the maximum of the second derivative.

The temperature dependence of both the transparency and threshold currents measured as explained above is shown in Fig. 15a in a semi-log plot. It is customary to express the temperature dependence of the threshold current over a certain temperature range through the empirical relation [Mc Ilroy 1985]

Figure 15.(a) Temperature dependence of transparency and threshold currents. (b) Empirical exponential model for transparency current. (c) Empirical exponential model for threshold current. (d) Expected Auger break point near 260 K for threshold current.

$$I_{th} \propto e^{T/T_{0,th}} \quad (30)$$

where the parameter $T_{0,th}$ is a measure of the degree of temperature dependence, with smaller values indicating a higher sensitivity. According to Eq. (30), $T_{0,th}$ is easily obtained from the reciprocal of the slope of a semi-log plot of the threshold current vs. temperature and break points occur where the slope changes its value. For our device, determination of such transitions was particularly difficult, since the resulting curve exhibits several possible break points in the whole temperature range, as may be observed from Fig. 15a. In fact, when applied to the experimental data, the model failed to explain the threshold current temperature dependence. On the other hand, the model fitted very well to the transparency current data, as shown in Fig. 15b. Two temperature break points were found at $T_{b1} = 91$ K and $T_{b2} = 250$ K. The values for $T_{0,tr}$ were 63 K, 316 K and -1602 K in the ranges $T < T_{b1}$, $T_{b1} < T < T_{b2}$ and $T > T_{b2}$, respectively. The inset illustrates that the model is excellent, since the fit residuals follow a very consistent random distribution in the whole temperature range, indicating the deviations can be completely attributed to noise. The applicability of Eq. (30) to the transparency current has been suggested in the literature [Higashi 1997]. However, this is, perhaps, the first time that direct experimental evidence has been reported. Therefore, it is possible to write

$$I_{tr} \propto e^{T/T_{0,tr}} \quad (31)$$

For the threshold current, a more suitable empirical model valid in almost the entire temperature range under consideration is given by

$$I_{th} \propto e^{(T/T_{0,th})^2} \quad (32)$$

The curve fits obtained are shown in Fig. 15c. Although the transition region near $T_b \approx 100$ K is not abrupt, as was the case for the transparency current fit using Eq. (31), the threshold current changes its temperature sensitivity from $T_{0,\text{th}} = 194$ K to 111 K below and above 100 K, respectively. However, in this case the residuals exhibit some structure, indicating the model does not explain the data in narrow temperature ranges. This consideration is particularly important near the predicted Auger recombination break point in the vicinity of 260 K for 1.55- μm lasers with undoped InGaAsP active regions [Haug 1985]. The wide-range temperature model given by Eq. (32) does not predict a break point in this range. However, using Eq. (30) for the threshold current data between 225 K and 300 K only, a break point can be detected at 261 K with $T_{0,\text{th}}$ equal to 100 K and 71 K for the regions below and above this point, in very good agreement with theoretical estimations [Haug 1985]. This is illustrated in Fig. 15d. Also, from Fig. 15c, the short straight line segment can be observed in the range from 20 K to 70 K. Applying Eq. (30) in this region, it was found that $T_{0,\text{th}} = 44$ K, although the fit is not good as can be seen in the residuals for the fit in this region. Other than these two narrow temperature ranges, it was very difficult to determine other regions that would be described by Eq. (30). Further measurements with smaller temperature steps would be required to accurately determine other possible transitions.

The above observations suggest that the transparency current exhibits a wide-range temperature dependence completely described by Eq. (31), while the threshold current exhibits both a long-range temperature dependence given by Eq. (32) and a narrow-range temperature dependence predicted by Eq. (30). This is consistent with the fact that the threshold current is not an intrinsic material parameter, due to its dependence on optical

losses, and therefore should be less sensitive to recombination rates variations in the active region. Yet, both currents predict a break point near 260 K, which is related to the predicted Auger break point. However, in the case of the transparency current, the large negative value obtained for $T_{0,\text{tr}}$ for $T > 250$ K does not have a clear physical interpretation, although it may be qualitatively stated that the transparency current is roughly independent of temperature above 250 K.

4.2 Differential Efficiency and Single-Mode Emission Wavelength

The estimation of the differential efficiency using Eq. (18) requires a clear definition of the parameter λ_0 . Since the FPL1055C is a multi-mode laser, estimation of the derivative

Figure 16. Above-threshold spectral measurements at 200 K at currents a) $I = I_{\text{th}} + 2$ mA, b) $I = I_{\text{th}} + 5$ mA, c) $I = I_{\text{th}} + 10$ mA, d) $I = I_{\text{th}} + 20$ mA, e) $I = I_{\text{th}} + 40$ mA, f) $I = I_{\text{th}} + 60$ mA.

of the L - I curve at high currents would lead to a poorly defined value for λ_0 as many modes are observed at such bias conditions. However, it was expected that the laser would operate in single-mode at currents slightly above threshold. In such current range λ_0 have a clearly defined value. Also, such current region can be used for finding $\Delta P/\Delta I$. While the method proposed is strict in the sense that the external differential efficiency is estimated for a single-mode, it is inefficient in practice. It requires current sweeps with concomitant spectral characterization, which imply a very long characterization time, especially if fine current steps are necessary. An alternate simple method was proposed for quick detection of the single-mode current range. Fig. 16 shows the current dependence of the laser spectra for currents above threshold. The plots were taken at 200 K. The evolution of the spectra is included for currents 2 mA, 5 mA, 10 mA, 20 mA, 40 mA and 60 mA above threshold. Up to 10 mA, the laser is clearly single-mode, with central wavelength of emission $\lambda_0 = 1497.52$ nm. Interestingly, at some point between 10 mA and 20 mA a second mode appears, as can be observed in Fig. 16d. However, consideration of the spectra at 40 mA reveals that the laser is again single mode at that current. This indicates that mode hopping has occurred. The new dominant mode occurs at $\lambda_0 = 1498.52$ nm according to Fig. 16e. Then, 60 mA above threshold, the simultaneous appearance of multiple modes is already obvious, as shown on Fig. 16f.

Figure 17. Correlation between current region with MSR > 3 dB and maximum positive curvature on dP/dI .

The mode suppression ratio (MSR) was calculated for the relative magnitudes between the main and the secondary mode for all currents. The result is shown in Fig. 17 along with the dP/dI curve calculated from the power resulting from integration of the spectral energy density. From the figure, it can be seen that the effect of mode hopping is to create a dip in the MSR curve around 20 mA [see also Fig. 16d]. At 40 mA, the MSR is ~ 8 dB while a minimum is observed for dP/dI , and finally approaches 0 dB at high currents as expected for multi-mode operation.

This analysis was performed at different temperatures and a similar trend was observed, although, in general, the minimum of dP/dI was observed for values of MSR as low as 3 dB. Based on these observations, an algorithm was specified to find a current range for estimation of the external differential efficiency under single-mode operations. According to this algorithm, the current range to be considered was that between the first maximum of dP/dI above threshold and the first minimum after this maximum. The underlying assumption is that, in this range, the MSR would be at least 3 dB. Once the current range

Figure 18. Above-threshold L - I characteristic differential analysis at (a) 300 K, (b) 120 K, (c) 70 K and (d) 30 K.

was known, the laser spectrum was measured using the current at the midpoint of the range for determination of λ_0 .

Fig. 18 shows the derivative analysis done to estimate the differential efficiency from the slope of the L - I curve above threshold. The estimations were limited to single-mode operation region as discussed before. Using this method, it was possible to measure the slope of the L - I characteristic down to 30 K (Fig. 18d). A current resolution better than 0.2 mA would be required to resolve the dP/dI maxima and minima at lower temperatures.

Figure 19. Temperature dependence of η_d as measured from the L-I characteristics, with a 5-segment linear fit.

The temperature dependence of the differential efficiency is shown in Fig. 19. The form of the curve clearly suggests multiple linear fits can be done in order to extract the temperature break points. A 5-segment linear fit was used in this case. The fit is very good even though the distribution of the residuals follows a periodic pattern in the entire temperature range. The temperature break points occur at 90 K, 128 K, 160 K and 240 K. The strong break points at 90 K and 240 K can be correlated with the temperature break points observed for the transparency current (see Fig. 15b). The weaker break points at 128 K and 160 K do not have a clear correlation, although a more careful examination of the threshold current may reveal such coincidences.

Figure 20. Temperature dependence of the differential efficiency at currents a) 20% above threshold, b) 40% above threshold, c) 60% above threshold, and d) 80% above threshold.

The temperature dependence of the differential efficiency is modified at higher currents.

Fig. 20 shows the temperature dependence on the differential efficiency evaluated at currents 20%, 40%, 60%, and 80% larger than threshold. Fig. 21 depicts the temperature dependence of the differential efficiency for currents well-above-threshold, evaluated at

Figure 21. Temperature dependence of the differential efficiency at currents a) 100% above threshold, b) 200% above threshold, c) 300% above threshold, and d) 400% above threshold.

current levels 100%, 200%, 300% and 400% larger than threshold. In the calculation of the efficiencies for both figures, the emission wavelength used corresponds to the peak emission at a bias current of 200 mA. The temperature dependence observed for a current of 20% above threshold shown on Fig. 20a resembles the curve provided on Fig. 19, as expected. At higher currents, the trend tends to change and eventually nearly disappears at an injection level 100% above threshold, as can be observed on Fig. 21a. At this current injection, the differential efficiency becomes nearly independent of temperature except for temperatures close to both 10 K and 300 K. At currents 200% or higher above threshold (see Figs. 21b-d), the observed differential efficiency decrease towards 10 K disappears and only the decrease above ~ 250 K persists.

The laser emission wavelength temperature dependence is depicted in Fig. 22a. It is evident that this parameter depends monotonically on temperature, with shorter wavelengths observed at lower temperatures. The temperature dependence of the associated transition energy given by $E_T = hc/\lambda_0$ is shown in Fig. 22b. For lasers with high internal efficiencies, at transparency, the quasi-Fermi levels in the active region are separated by a slightly larger potential than that associated with the material bandgap

Figure 22. a) Single-mode emission wavelength. b) Transition energy associated with single-mode emission wavelength.

energy, given by E_g/q . However, lasing occurs only after the material gain is increased to the point at which the optical losses are overcome. In the process, the gain spectrum broadens and the maximum gain occurs at the energy $E_T > E_g$. Thus, if the gain spectrum is sufficiently narrow and the threshold current is not far from transparency, the observed transition energy associated with single-mode operation should be close to the active region bandgap energy. The transition energy temperature dependence was fitted to the Varshni's formula [Varshni 1967] $E_g = A + (BT^2)/(T+C)$ used to estimate the bandgap energy temperature dependence in InGaAsP compounds [Liu 2005]. This fit is presented in Fig. 22b. It was found that $A = 0.865$, $B = 3.615 \times 10^{-4}$ and $C = 195.526$. Even though the residuals exhibit a clear structure indicating the model is not fully adequate, the empirical relation is still useful since the residuals are very small. Alternatively, the bandgap energy can be estimated from the terminal voltage in temperature regions where the laser characteristics can be well described within the ideal diode approximation. Under such condition, the terminal voltage should be very close to the quasi-Fermi level separation in the active region. Thus, the voltage at transparency is nearly equal to the

Figure 23. Associated transition energy temperature dependence with fit to Varshni's formula. The threshold and transparency terminal voltages are also used to estimate the band gap potential.

bandgap potential if the internal efficiency is high. A similar assumption is not true for the voltage at threshold since the effect of gain, loss and current injection must be taken into account for this case. Both estimates for the bandgap potential are shown in Fig. 23 along with transition energy curve. The estimates for the transition energy and for the bandgap voltage at transparency are in close agreement in the range from 150 K to 250 K. Indeed, the FPL1055C exhibited the lower values for the ideality factor in this range, as will be discussed ahead. Below 150 K, the device terminal voltage at transparency is much larger than the voltage corresponding to the transition energy. This is attributed to additional voltage drop across the layers outside the active region contributing to the overall terminal voltage. Most likely, this additional voltage drop occurs on the device metal-semiconductor junctions due to the contact resistance increasing with temperature. Above 250 K, the transparency terminal voltage predicts significantly smaller bandgap energy. The reason for this behavior is not understood. From Fig. 23, it can also be seen that the threshold terminal voltage always overestimates the bandgap, as expected from the contribution of the optical loss.

Figure 24. First derivative of V - I characteristic from 320 K down to 15 K. The device terminal series resistance can be estimated from the derivative values at high currents.

4.3 Series resistance

The series resistance r_s is a critical parameter for operation of lasers at cryogenic temperatures. A high series resistance can severely limit possible applications of semiconductor lasers at low temperatures. Experimental determination of this parameter was an important objective of the present work. The method of extraction proposed here accounts for possible large values of series resistance by discarding assumptions often made for explaining laser performance at ambient temperatures.

The temperature dependence of the dV/dI vs. current characteristic for the FPL1055C is depicted in Fig. 24 in a log-log plot. The “kink” at threshold can be observed as a discontinuity near 60 mA, 40 mA, 20 mA, and 12 mA at 320 K, 300 K, 240 K, and 200 K, respectively. The “kink” is no longer distinguishable at lower temperatures. While the derivatives are nearly independent of the current above threshold at high temperatures, they exhibit an increasingly stronger current dependence as the temperature is reduced. The effect is more pronounced for the derivatives below threshold. In this range, the current dependence is evident even at high temperatures. For this particular device, the

trend indicates that the sub-threshold derivatives would become current-independent at some temperature above 320 K. All these observations suggest that, in general case and contrary to some literature sources [Barnes 1976], [Coldren 2012], the series resistance cannot be estimated from dV/dI values near threshold, unless the derivatives exhibit current-independence at the temperature of interest.

Alternatively, the more general method suggested in this work would produce better estimates in a wider temperature range since the derivatives are expected to stabilize above a certain critical current level. Nonetheless, this critical level was not found for the device at any temperature. The derivatives keep decreasing for currents as high as 190 mA and, as noted before, the effect is more pronounced at lower temperatures. Moreover, the final derivative values at 190 mA have lower values at cryogenic temperatures than the corresponding values at room temperature. In other words, the series resistance can be lower at lower temperatures for sufficiently high currents, a rather unexpected result. This is better illustrated in Fig. 25, where the series resistance was calculated at fixed current levels for all temperatures. Indeed, the series resistance at low temperatures is lower than

Figure 25. Series resistance values estimated at different current levels from dV/dI plots.

the corresponding value at room temperature at high currents. In addition, it can be seen that the series resistance steadily drops at temperatures below $\sim 80 - 90$ K regardless of the current level. The reason for this transition is unknown, but it is strongly correlated with the break points for transparency current, threshold current and differential efficiency, occurring at a similar temperature.

4.4 Shunt resistance and ideality factor

The shunt resistance and the ideality factor were estimated by fitting Eq. (29) to I - V curves using the series resistance value obtained at 180 mA. Fig. 26 shows these curves for 300 K, 200 K, 100 K and 40 K. The fit converged for temperatures below 260 K down to 40 K. At 260 K or higher, the fit failed to explain the data points corresponding to very low currents. This limitation is very clear at 300 K as can be observed from Fig. 26a. The temperature dependence for both parameters is shown in Fig. 27. A five-segment linear fit performed for the ideality factor is shown in Fig. 26b. The fit is excellent as can be seen from the virtually random distribution of the residuals. Using this fit, temperature break points occur at 58 K, 130 K, 159 K and 251 K. From these, the break points at 130 K, 159 K and 251 K are strongly correlated with the break points detected in the analysis of the external differential efficiency (Fig. 19). In addition, as noted before, the temperature range for the lowest observed ideality factor is correlated with the temperature range where the transition energy and the transparency terminal voltage agree very well in estimating the active region bandgap. Thus, a purely electrical model may be used to estimate the device material bandgap, although the temperature range for its validity turned out to be very limited for our device.

Figure 26. I - V characteristic with sub-threshold fit to electrical model at (a) 300 K, (b) 200 K, (c) 100 K and (d) 40 K.

Figure 27. (a) Temperature dependence of shunt resistance. (b) Temperature dependence of ideality factor with 5-segment linear fit.

4.5 Analysis of the Temperature Dependence of Laser Parameters

4.5.1 Effect of Tunneling on Single-Mode Spectra and Ideality Factor

As presented before, Fig. 13 depicts the measured I - V curves in the full temperature range in a semi-log plot. The plot also includes the voltages and currents corresponding to the detected transparency and threshold currents, as well as those points corresponding to the voltage equivalent to the energy of the single-mode transition through the relation $V = E_T/q$. In all plots, the “voltage pinning” occurring at threshold is very evident for most of the curves, although the effect fades out at lower temperatures and virtually disappears below 40 K. Perhaps more interesting is the corresponding trace for the detected transparency current. It appears near the middle between the strong knee at very low bias and the threshold current. It is also evident how the distance between threshold and transparency current is more or less constant along the curves, but it quickly increases at high temperatures, where it can be observed that the threshold current increments much faster. This is the signature of the dramatic increase in the Auger processes occurring at high temperatures. Thus, it is clear that Auger does not affect the transparency current significantly. Also, the transition from a diffusion-regime current to a tunneling current is very evident at 40 K and below, since the slopes of the I - V curves below 55 K are nearly independent from temperature and more depend on voltage, which corresponds to the onset of tunneling across the junction [Casey 1996]. Another evidence of tunneling can be obtained from Fig. 27b, where it can be observed that the ideality factor increases dramatically at temperatures below ~ 60 K. The high values of the ideality factor at low temperatures are indicative of a tunneling mechanism of conductivity [Eliseev 1997].

Tunneling is a process that also has a strong bias dependence. The characteristic behavior of band-to-band tunneling at low bias was not observed for the FPL1055C. For this type of tunneling, a short region of negative resistance at low bias should occur and become unnoticeable at higher bias [Esaki 1958]. In addition, this type of tunneling is inherently non-radiative. In contrast, band-impurity tunneling can occur both at low and moderate bias and carriers can also recombine radiatively in order to generate light [Chynoweth 1961]. Fig. 28 sketches this type of tunneling process in a band energy diagram for a junction at intermediate or low bias. An electron initially on the n-side of the junction can tunnel to an impurity, denoted as A, and then recombine from this point with a hole. Similarly, a hole from the p-side can tunnel to an impurity level on the n-side (point B) and then recombine with an electron. Other possible recombination paths can occur across the band gap through intermediate steps. These steps can also radiate, although the associated radiation will not be favored in a laser since energy associated with these

FIG. 1. Diagram illustrating proposed mechanisms for the excess current flow.

Figure 28. Band-Impurity tunneling energy diagram. From [Chynoweth 1961]

transitions is much smaller than the material band gap.

The above discussion is relevant because the type of tunneling observed on the FPL1055C may be radiative and may actually be assisting the process of stimulated emission. In Fig. 22a, the small discontinuity for the single-mode emission wavelength at 40 K or lower temperatures is strongly correlated with the transition to tunneling as discussed from Fig. 13. This coincidence suggests band-impurity radiative tunneling may be occurring at temperatures ~ 40 K or lower.

4.5.2 Effect of Non-Radiative Recombination on Threshold Current

The break point analysis performed on all laser characteristics reveal that most parameters are well behaved at a temperature immediately below 240 K. In this region, both the threshold and transparency currents can be characterized by a constant characteristic temperature. This can be verified in Fig 15b and Fig. 15d. For this range, $T_{0, \text{tr}} = 316$ K for the transparency current and $T_{0, \text{th}} = 100$ K for the threshold current. Above 240K, the transparency current exhibits a break point at 250 K associated with inter-valence band absorption (IVBA) [Adams 1980] while the threshold current presents a break point at 261 K associated with Auger recombination [Haug 1985]. Also, at 240 K, the differential efficiency peaks as can be observed from Fig. 19, and the ideality factor is minimum, as can be verified from Fig. 27b. All these observations indirectly suggest that the FPL1055C is operating almost ideally in the vicinity of 240 K. Under this assumption, it is possible to estimate the effect of diverse detrimental processes by extrapolation.

Figure 29. Threshold current and extrapolated threshold current matched at 240 K.

The effect of Auger recombination can easily be observed in the threshold current at high temperatures. The current component associated with this effect can be isolated by extrapolating the current characteristics from a temperature where the Auger effects are negligible, presumably 240 K. Using Eq. (30) with $T_{0,th} = 100$ K and $I_{th,0} = 1.673$ mA, the empirical curve was fixed to the measured threshold current observed at 240 K. Then, both the measured and the empirical threshold currents were plotted in Fig. 29. Due to the predominance of the Auger effect on threshold current, the observed difference between the measured and the extrapolated current above ~ 260 K can be attributed to this effect. Further support for this conclusion arises from the behavior of the ideality factor in this temperature range. Fig. 27b clearly illustrates that the ideality factor increased above ~ 250 K. According to the theory of carrier transport across semiconductor junctions, the effect of recombination in the junction depletion region, either radiative or non-radiative, will increase the current necessary to maintain the required minority carrier injection across the junction as dictated by the law of the junction. This excess current leads to an

increase of the ideality factor. Indeed, such an increase can be observed from Fig. 27b. above 250 K.

In Fig. 29, it can also be noted that the measured threshold current exceeds the extrapolated level for temperatures below ~ 220 K. This difference peaks near 100 K and dies at temperatures close to 20 K where, again, the measured and interpolated values agree very well. Again, for this excess current, a concomitant increase in the ideality factor can be observed in the range from 220 K down to ~ 130 K, as can be verified on Fig. 27b. However, below 130 K the ideality factor increases at a higher rate down to ~ 60 K, and then essentially blows up at lower temperatures as a result of tunneling. Additional insight in this region can be provided by analyzing the temperature dependence of the pre-exponential factor I_0 used in Eq. (29) and shown in Fig. 30, and by observing the excess voltage appearing on the laser below 150 K in Fig. 23, where the transparency voltage departs from the expected equivalent voltage for the single-mode emission wavelength. This voltage difference can also be appreciated in the I - V characteristic in Fig. 13 from the lines representing the transparency and transition energy voltage-current points.

The pre-exponential factor of Eq. (29) contains the dependence of the I - V curve on band gap and temperature through its dependence on the active region intrinsic carrier concentration n_i . For lasers, it is well known that the dependence of the pre-exponential factor goes approximately as n_i as opposed to devices with no significant recombination currents dominated by diffusion where I_0 depends on n_i^2 . Regardless of the case, it is clear that this dependence is monotonic with respect to temperature. However, in Fig. 30, I_0 no longer decrease at temperatures below ~ 130 K, but rather increases reaching a peak at ~ 90 K. This unphysical behavior suggests that the electrical model proposed in Eq. (29) does not account for this excess voltage and that, in such case, it leads to an overestimation of the ideality factor. All this evidence points to the existence of such excess voltage that appears across the device terminals but is not originated in the active region at temperatures below 130 K. If this is true, this voltage can account for the enhanced growth rate of the ideality factor in this region. Such effect would mask the

Figure 30. Temperature dependence of the pre-exponential factor I_0 in Eq. (29).

otherwise slower growth of the ideality factor in such region, which may correspond to a possible increased rate of non-radiative recombination.

Based on the former discussions, it may be postulated that at temperature below ~ 220 K, there is a non-radiative recombination process slowly increasing its rate as the temperature is decreased, and reaches a maximum rate at ~ 100 K. As explained before, a small increase in the ideality factor should be accompanying such behavior, but the excess voltage in the device below 130 K and the onset of tunneling below 50 K completely preclude such confirmation. Since the active region bandgap is monotonically increasing at lower temperatures, this non-radiative recombination mechanism may be associated with a steady increase in the density of impurity recombination centers being activated by the stretching energy band gap. Thus, recombination due to Shockley-Read-Hall processes may explain the excess threshold currents observed below 220 K.

An possible alternate explanation of the apparent increase in threshold current below ~ 100 K could be related to possible variations of gain through changes in stress or strain in the active region caused by thermal stresses. Such effect could reduce the bimolecular recombination coefficient on that temperature range, leading to a reduction in the radiative efficiency. However, confirmation of such hypothesis would require further investigation of the device internal structure and more advanced characterization. This is beyond the scope of the present work.

4.5.3 Effect of Carrier-Dependent Losses on Differential Efficiency

The laser injection efficiency, η_{inj} , is defined as the fraction of injected current that generates carriers (electron-hole pairs, or e-h pairs) in the active region, including the

ones participating in both radiative and non-radiative recombinations. Experimentally, η_{inj} can be extracted from the L - I characteristic of multiple lasers fabricated from the same wafer having different cavity lengths [Biard 1964]. This is possible because η_{inj} is intrinsically related to η_d , which is dependent on the laser cavity length and other material parameters through the well-known relation

$$\eta_d = \eta_{inj} \frac{\gamma_{out}}{\langle \gamma_c \rangle} = \eta_{inj} \frac{\alpha_m}{\alpha_m + \langle \alpha_i \rangle} \quad (33)$$

where γ_{out} is the *output-coupling rate* and γ_c is the *average cavity decay rate* [Liu 2005], in units of s^{-1} ; α_m is the *mirror loss* and $\langle \alpha_i \rangle$ is the *average internal loss*, in units of m^{-1} . Decay rates and losses are connected through the optical mode *group velocity* in the cavity v_g , through the relations $\alpha_m = v_g \gamma_{out}$ and $\alpha_m + \langle \alpha_i \rangle = v_g \gamma_c$. In these relations, the group velocity is more appropriate than the phase velocity, since the former determines the speed at which the energy of the mode is moving in the waveguide.

Taking the inverse of Eq. (33), it is clear that

$$\frac{1}{\eta_d} = \frac{1}{\eta_{inj}} \cdot \frac{\langle \alpha_i \rangle}{\alpha_m} + \frac{1}{\eta_{inj}} = \frac{1}{\eta_{inj}} \cdot \frac{\langle \alpha_i \rangle}{\ln(R)} L + \frac{1}{\eta_{inj}} \quad (34)$$

In Eq. (34), the relation $\alpha_m = \ln(1/R)/L$ has been used, where R is the facet mirror reflectance and L is the laser cavity length. It is easily seen from Eq. (34) that the y-intercept of $1/\eta_d$ vs. L plot yields the inverse value of η_{inj} and, using this value, the slope of this relation can be used to estimate $\langle \alpha_i \rangle$, which accounts for the number for photons generated that did not contributed to the output light due to the optical internal losses

within the cavity. Thus, the experimental estimation of both η_{inj} and $\langle\alpha_i\rangle$ requires the availability of lasers of different cavity length made of the same epitaxial material.

However, the simple model provided above has several problems [Higashi 1997]. First, the method requires several devices with assumed identical parameters with the exception of their cavity lengths. Thus, the uncertainty associated with the measurement of this parameter for individual devices together with variation on any other laser parameters affecting the loss, directly affect the uncertainty of the loss estimation for an individual device [Andrekson 1992]. Second, the method assumes the internal loss is independent of the cavity length. However, it has been shown that inter-valence band absorption (IVBA) has a dependence of the threshold carrier concentration, which in turn depends on the cavity length [Asada 1981]. Moreover, in the case of long-wavelength MQW lasers with InGaAsP barriers, IVBA arising from the inter-well barriers can be severe owing to the large spatial overlap of these layers and the optical mode [Tanaka 1993]. Based on these considerations, it is clear that a more general model is necessary if the effects IVBA in the active region and barriers is to be considered.

Simple models have been provided to account for the effects of IVBA in the active region [Adams 1980]; in the active region and claddings in separate confinement heterostructures (SCH) [Andrekson 1992] and active region, barriers and claddings for MQW devices [Tanaka 1993]. Since the FPL1055C belongs to the latter category, the model of Tanaka will be used in this work. In this model, the *net internal loss* is given by

$$\alpha_i = \alpha_0 + \Gamma_w \alpha_w + \Gamma_c \alpha_c \quad (35)$$

where α_w is the loss in the wells, α_c represents for the loss in the claddings, Γ_w is the well confinement factor and Γ_c is the cladding confinement factor. Both Γ_w and Γ_c should be calculated independently with respect to the same optical mode. Also, to a first approximation [Tanaka 1993], both α_w and α_c depend on carrier density through the relations

$$\alpha_w = \alpha_{w0} + bN \quad (36)$$

$$\alpha_c = \alpha_{c0} + cN \quad (37)$$

In Eq. (36) and Eq. (37), α_{w0} and α_{c0} are the losses per well and in the cladding, respectively, in the absence of carrier injection. For α_c , proportionality to the well carrier density has been assumed from the proportionality between the barrier carrier density and the well carrier density. In both Eq. (36) and Eq. (37), the dependency on N represents the absorption due to IVBA, acceptor-to-band absorption and free-carrier absorption. Thus, direct substitution of Eq. (36) and Eq. (37) into Eq. (35) would yield an expression for the carrier-dependent *average internal loss* given by

$$\langle \alpha_i \rangle = \alpha_0 + \Gamma_w(\alpha_{w0} + bN) + \Gamma_c(\alpha_{c0} + cN) \quad (38)$$

Therefore, Eq. (33) can be re-written as

$$\eta_d = \eta_{inj} \frac{\alpha_m}{\alpha_m + \langle \alpha_i \rangle_{th}} = \eta_{inj} \frac{\alpha_m}{\alpha_m + [\alpha_0 + \Gamma_w(\alpha_{w0} + bN_{th}) + \Gamma_c(\alpha_{c0} + cN_{th})]} \quad (39)$$

where N_{th} , the carrier density at threshold has been used, since carrier density clamps after stimulated emission dominates. Eq. (39) indicates that, if carrier-dependent losses are strong, η_d should decrease. Using a very similar method, Adams *et al.* attributed the

decrease of the external differential efficiency above 250 K observed for InGaAsP compounds to the effects of IVBA absorption [Adams 1980]. Thus, it is possible to attribute the observed decrease of the differential efficiency of the FPL1055C (Figs. 19, 20, 21) to such effect.

4.5.4 Series Resistance

A visual inspection on Fig. 13 shows that the device makes the transition to the portion of the I - V curve dominated by series resistance at different currents, a characteristic that is perhaps more clearly identified in Fig. 24. It is also clear from Fig. 13 that the series resistance is smaller at lower temperatures, as indicated by the higher slopes observed for the curves in this temperature range. These results are contradictory to predictions based on mobility considerations and carrier freeze-out [Katz 1985]. Moreover, from Fig. 25, it is clearly seen that the series resistance exhibits a non-linear dependence on bias current, and the degree of non-linearity increases at lower temperatures. To complicate things further, the possible existence of the excess voltage at temperatures below 140 K may also be affecting the estimated series resistance. Indeed, the series resistance exhibits peak values at ~ 90 K, regardless of the current, that are nearly concomitant to the peak associated with the excess threshold current occurring at 100 K. It is also clear that below 90 K the series resistance values for different currents converge again and decrease monotonically again. These observations suggest that, ideally, the series resistance of the FPL1055C may be monotonically decreasing at lower temperatures and should have little current dependence. This increase in conductance is consistent with the theoretical estimations for the mobility, since at lower temperatures, both lattice and impurity ionization scattering should diminish (impurities are no longer ionized below some point)

and therefore the mobilities for both types of carriers should increase. On the other hand, carrier freeze-out would not be observed if the transport layers in the laser are heavily doped.

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CHAPTER 5. CONCLUSIONS AND FUTURE WORK

The COVEGA FPL1055C 1.55- μm MQW ridge-waveguide Fabry-Perot high-power laser has been electrically and optically characterized from room temperature down to 10 K. The overall experimental results indicate that even though the FPL1055C was designed for room-temperature applications, it is nonetheless suitable for operation at cryogenic temperatures. The device exhibits a peak external differential efficiency at ~ 90 K and features a very low series resistance in the whole temperature range.

Experimental characterization methods used at room temperature were applied systematically down to 10 K. In addition to the conventional parameters extracted from the laser L - I / I - V /spectral characteristics, a novel method for estimating the transparency current has been proposed. Using this novel technique, the transparency empirical relation $I = I_{\text{tr},0} \exp(T/T_{0,\text{tr}})$ proposed by [Higashi 1997] has been found in agreement the experimental data. The obtained temperature dependence for the laser parameters has been explained with simple empirical models, where possible. Relations between the parameters have been suggested, based on correlations of the break points occurring at certain temperatures.

Several other important findings have been made. These have been discussed in detail as part of the analysis performed on the data.

As a result of this work, it has been immediately realized the need to further improve the characterization setup. There are several important considerations. First, it is possible to expand the existing setup to implement the direct detection of the first and second

derivatives of the $L-I$ and the first derivative of the $I-V$ curves using lock-in amplification techniques. In the current setup, such analysis has been performed numerically and therefore, a significant amount of imprecision may have been introduced in the calculations. Implementation of such technique would require an additional lock-in amplifier to generate the modulation signal to the laser and to recover the harmonics present in the voltage and optical power signals.

Another important consideration for the future is to enhance the capability of the setup to perform gain estimations through the Hakki-Paoli method [Hakki 1973]. Although this was not attempted in the present setup, the current sensitivity of the setup allowed the optical power to be detected even under very small bias conditions (>1 mA). If the gain is measured and the transparency current estimation proposed in this work is correct, all the information needed to fully explain the laser performance using empirical relations would be provided. Moreover, such measurements would allow the decoupling of the effects of increasing loss or decreasing gain as the temperature is increased. However, implementation of Hakki-Paoli method would also require control of the laser polarization. An additional stage with wave plates and polarizers is necessary to achieve such control.

Finally, given the amount of experimental data that is necessary for completing an experiment, it would be very convenient to fully automate the experimental setup. The present version of the system is limited by the optical alignment, which is manual and has to be repeated at all temperatures prior to characterization. This seriously slows down the process of collecting the data. Full automation would dramatically accelerate the data acquisition process.

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