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An experimental investigation of tunable laser diodes based on multiple etched slots

Thesis
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Declaration

This thesis has not been submitted as an exercise for a degree in this or any other university. The work described in this thesis is entirely my own, with exception of assistance recognised in the acknowledgements and the collaborative work noted in the publications. I agree that Trinity College may lend or copy this thesis on request.
Dedicated to the memory of a great friend Michael Doherty – R.I.P.
Summary

Widely tunable semiconductor lasers will play a critical part in future technologies. Tunable lasers are rapidly replacing fixed wavelength lasers in dense wavelength division multiplexing (DWDM) optical communications. The performance specifications of tunable lasers are the same as fixed wavelength specifications plus additional specifications that include: wavelength tuning range; wavelength switching speed; and minimum wavelength spacing. Tunable laser diodes (TLD) have been used in optical networks for some time now starting with devices with small wavelength coverage and moving towards full band coverage.

Wavelength-agile networks are also simplified with tunable lasers. Reconfigurable optical add-drop multiplexers (ROADMs) and wavelength-based routing enable service providers to offer differentiated services, meet the ever-increasing demand for bandwidth and deliver all-optical networking. Tunable lasers are key to addressing this growing need to reconfigure networks remotely. The use of widely tunable lasers helps maximize existing network resources. The ability to dynamically provision bandwidth provides the ability to optimize the network configuration to meet demand. Widely tunable lasers move traffic from overcrowded channels to unused channels and are becoming essential for the network architecture.

Future DWDM networks will make more use of wavelength converters to increase network flexibility. Wavelength converters, such as optical-electronic-optical (OEO) converters that have the ability to detect a high data rate signal on any input wavelength channel and to convert to any output wavelength channel, will use tunable lasers. Future uses for tunable lasers will also include packet based selection of the wavelength on which the packet is to be transmitted. The tunable laser switching speed for these applications will be of the order of micro-seconds or longer. They will typically need to be widely tunable, i.e. tunable over a full C or L band and should be tunable to the 50 GHz channel spacing. In some ultra dense wavelength division multiplexing (UDWDM) applications, channel spacing of 25 GHz and eventually as close as 12.5 GHz will be required.

Tunable lasers will also be used as a means to reduce costs as sparing lasers in wavelength division multiplexing (WDM) systems. New approaches to data transmission such as coherent WDM (CoWDM) require discrete tuning between
particular wavelength channels on a grid. Additionally, there is an urgent need to integrate semiconductor lasers with other optical components such as amplifiers, modulators and detectors in order to reduce chip cost, system size and complexity. Tunable lasers are also needed in other important markets such as trace gas detection for environmental emission monitoring.

Laser operation requires optical feedback which is conventionally obtained in a semiconductor Fabry-Pérot laser by cleaving the ends of the laser waveguide along either (011) or (01-1) crystallographic planes to form two semi-reflecting facets. However, due to the need for cleaving, it is difficult to integrate these lasers with other optical components on a single chip.

Distributed-Bragg-reflector (DBR) lasers and distributed feedback (DFB) lasers, which employ a series of small refractive-index perturbations to provide feedback, do not rely on cleaved facets and therefore can be integrated with optical amplifiers and modulators.

However, complex processing with multiple epitaxial growth stages is required for fabricating these lasers. Another method to obtain feedback is to etch a facet. However, this approach is limited by difficulties in achieving the smoothness and verticality of the etched facet particularly for structures based on InP materials.

Previously it was shown that by introducing a shallow slot into the active ridge waveguide of a laser, the longitudinal modes of the Fabry-Perot (FP) cavity were perturbed according to the position of the slot with respect to the cleaved facets. By judicious placement of a sequence of low-loss slots with respect to the facets pre-selected FP modes could be significantly enhanced leading to robust single frequency lasing with wide temperature stability as well as tuning with fast switching characteristics. More recently, we have characterized the properties of slots which are etched more deeply namely to the depth of, but not through, the core waveguide containing the quantum wells. In that case, the reflection of each slot is of the order of ~1% with transmission of ~80% and the slot will strongly perturb the mode spectrum of the FP cavity by creating sub-cavities. The loss introduced by the presence of the slot is compensated by gain in the laser. An array of such slots can provide the necessary reflectivity for the laser operation independent of a cleaved facet where the gain between the slots compensates for the slot loss producing an active slotted mirror region. Such a mirror has been used in conjunction with a cleaved facet permitting the integration of a photodetector with the laser. As the laser output facet is not cleaved
this can provide a much easier integration platform on which complex devices such as Mach-Zehnder modulators (MZI) and semiconductor optical amplifiers (SOA) can be monolithically integrated with the laser to reduce chip cost and complexity significantly. In this thesis tunable lasers with over 40 nm tuning and high side mode suppression ratio (SMSR) are described. The monolithic integration of an SOA which is used to both increase and balance the output optical power of different channels is also shown to introduce our integration platform.
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Chapter 8 - Conclusion
Chapter 1 - Introduction

The first semiconductor laser (laser diode) was demonstrated in 1962, shortly after the first Ruby laser which was considered the first successful laser. In the 1970s the double heterostructure laser fabricated from AlGaAs/GaAs was demonstrated and very quickly became commercialised as it had a number of advantages over other types of lasers which included, size, power conversion efficiency, ability to pump by injecting current, lifetime reliability, and wavelength flexibility. Laser diodes are now the most common laser types in existence and are found in a host of applications from printers and CD players to optical communications and gas sensing applications. The ability to control the wavelength independently of optical power adds a new dimension to the laser diode. This type of laser diode, the tunable laser diode, has found applications mostly in optical communication systems with the research in this area being driven by the increasing demand placed on optical communication systems to increase bandwidth and reduce latency. The advent of wavelength division multiplexing (WDM) and coherent optical detection schemes have addressed these problems with tunable laser diodes as the key source [1, 2]. A schematic of a tunable laser output power and wavelength is shown below in figure 1.1 which is taken from [3]. Figure 1.1 (a) shows an idealised tunable laser diode where the optical power is dependent only on the laser current and the wavelength is dependent only on the tuning current, (b) shows the same idealised case where any change in the tuning current only changes the output wavelength and leave the optical power unchanged. The wavelength should show a smooth and hysteresis-free dependence on the tuning current. Figure 1.1 (c) again shows the idealised case where any change in the laser drive current changes only the optical power and leaves the wavelength unchanged. In this case the optical power is low until the threshold position is reached and then increases with increasing drive current. This ideal relationship cannot be obtained as the wavelength and optical power are coupled and any change in the wavelength tuning current will change the optical loss and therefore the optical power of the tunable laser, and changes in the laser drive current can affect the temperature of the device with will change the wavelength position. In order to remove this coupling between the power and wavelength multi-section devices were devised where the wavelength tuning current and optical power current controls are spatially separated.
Figure 1.1. (a) — Ideal relationship between laser current and optical power on one hand and tuning current and wavelength on the other, (b) — wavelength and power versus tuning current, (c) — wavelength and power versus laser drive current ($I_\text{th}$ is the threshold current).

Changing the current injected into a laser diode changes other characteristics of the laser i.e. the laser linewidth, linewidth enhancement factor, and FM modulation bandwidth. Therefore, to produce a tunable laser diode it is better to have a specific application in mind and to tailor the tunable laser to suit the application. An overview of the applications of tunable lasers and the characteristics that are most important are given in figure 1.2 below.

Figure 1.2. Major applications and specific demands on performance of tunable laser diodes from [3].
When choosing a tunable laser for a specific application the device performance is of high importance as different tunable lasers have different strengths and weakness. For WDM, for example, a large tuning range with uniform optical output power and good FM modulation bandwidth is required. For device characterisation, as shown later in chapter 4, continuous tuning is required and also a large tuning range.

The objective of this thesis was to understand the physics behind a new type of tunable laser diode which can be monolithically integrated with other photonic components on photonic chips to reduce size, complexity and overall chip cost. As the target applications are WDM and coherent optical communications then most of the device performances on the left of figure 1.2 are required for our tunable laser diode. This thesis deals with the first four of the tunable laser device characteristics namely, continuous tuning, tuning range, optical power, and linewidth. The switching speed of the laser will also be dealt with. The FM modulation bandwidth will not be addressed here.

Chapter 2 introduces various laser diodes starting with single mode laser diodes like distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers. Then tuning mechanisms to change the wavelength position are introduced where the different regimes of continuous, discontinuous and quasi-continuous tuning are introduced. The electronic and thermal control of the output wavelength is then introduced and the free carrier plasma effect, the mechanism used to achieve tuning in semiconductor laser diodes, is described. Vernier effect tuning is then introduced which extends the tuning range above the refractive index change tuning that the free carrier plasma effect gives. A tunable laser diode which makes use of this mechanism in then described. Finally other types of tunable lasers are described the most important being the external cavity laser (ECL) as this is used extensively in chapter 4 for device characterisation.

Chapter 3 introduces the scattering matrix method (SMM) and transmission matrix method (TMM) for simulating laser diodes. This chapter shows that the SMM is a better method to the TMM for devices with large distances between inputs and outputs as these distances introduce numerical instabilities into the TMM.

Chapter 4 deals with Fabry-Pérot (FP) laser measurements which are important in the design of tunable laser diodes. The linewidth enhancement factor is introduced and a new method to measure it is given and compared with some widely used methods. The new method presented shows an improvement at low resolution.
bandwidths of the optical spectrum analyser (OSA) used to measure the laser spectrum. The waveguide loss is then introduced and two different methods to measure it are described. The advantages of these methods are that only one facet is required as currently the waveguide loss is commonly determined from the reflection spectrum where as we propose a method to calculate the loss from the amplified spontaneous emission (ASE) spectrum. The spontaneous emission factor and quasi-Fermi level separation are determined using a new method. The coupling efficiency and internal quantum efficiency is then determined for a FP laser diode. The coupling efficiency is an important factor as it is needed to determine the real power out of the tunable lasers described in chapters 6 and 7 from the coupled output power.

Single slot laser diodes are presented in chapter 5 and the SMM is again used to determine the optimal slot position, depth and width of the slot in the laser cavity. The concept of angled slots is also introduced here and shown to have advantages over straight slots. Experimental investigations on single slot laser with both straight and angled slots are described and the Fourier expansion is shown to determine slot positions inside the laser cavity with good accuracy. The reflection, transmission and slot width are all determined from a method proposed in this chapter from the ASE spectrum.

Chapter 6 introduces the tunable laser diode produced by etching multiple slots into the waveguide ridge of a FP laser diode. Firstly just one section with etched slots is simulated and experimentally investigated. This leads to the addition of more sections giving more wavelength control and finally giving the optimal design of three sections with nine slots in both end sections with a gain section in between. The last part of chapter 6 deals with the integration of the laser device with other photonic components such as a photodetector and semiconductor optical amplifier (SOA). This adds uniformity across the wavelength range of tuning and also increased the output power of each super-mode.

Chapter 7 continues the characterisation of the three section laser described in chapter 6. The continuous tuning is analysed by changing the injection currents into both end sections in a linear fashion. A four section laser is then introduced to increase the tuning range by making use of the quasi-continuous tuning method by changing the injected current in a small section beside the gain section which is electrically isolated from the gain section. The linewidth of the three section laser is
determined from the self-homodyne method and the switching speed is determined by the optical heterodyne method for two channels.

Chapter 8 gives some conclusions reached over the course of this work and some future work which is ongoing such as the monolithic integration of the tunable laser with a Mach-Zehnder interferometer (MZI).
References


Chapter 2 - An Introduction to Tunable Lasers

In this chapter various types of lasers are considered as an introduction to tunable laser diodes. First single mode operation is realised through periodic refractive index changes leading on to two of the most widely used and successful single mode laser diodes, the distributed Bragg reflector (DBR) and the distributed feedback laser (DFB). The electronic control of laser diodes is then examined and in particular how changes to the injected carrier density and temperature control the wavelength output of the laser. The Vernier tuning mechanism is then introduced to greatly expand the wavelength range over which lasers can tune and the sampled grated distributed Bragg reflector laser is introduced as an example laser employing Vernier tuning. Other tunable lasers are also introduced as some such as the external-cavity laser are used further in this work.

Single mode laser diodes

An excellent introduction to single mode and tunable laser diodes can be found in [1, 2]. From [3, 4] for good single mode operation the cavity gain for the lasing mode should exceed that of all other modes by about 5 cm\(^{-1}\), compared to about 0.01 cm\(^{-1}\) for the modal gain. Considering a structure in which the refractive index varies periodically in the propagation direction z, the refractive index is

\[
n(z) = n_{\text{eff}} + \frac{\Delta n}{2} \cos(2\beta_0 z)
\]  
(2.1)

where \(\Delta n/2 < n_{\text{eff}}\). The parameter \(\beta_0\) is the Bragg propagation constant and is related to the period of the structure A by
\[ \beta_0 = \frac{M \pi}{\Lambda} = \frac{2\pi}{\lambda_B} n_{\text{eff}} = k_0 (\lambda_B) n_{\text{eff}} \]  \hspace{1cm} (2.2)

where \( \lambda_B \) is the Bragg wavelength in free space, \( k_0(\lambda_B) \) is the free space propagation constant for wavelength \( \lambda_B \) and \( M \) is the period order. For a first order structure we have

\[ \Lambda = \frac{\lambda_B}{2n_{\text{eff}}} \]  \hspace{1cm} (2.3)

therefore the period is equal to half the wavelength in the structure. The periodic structure couples forward and backward-going waves in the structure. If we suppress the time factor \( \exp(-i\omega t) \) and keep in mind that all the transverse and lateral variations are neglected, the electric field is

\[ \frac{d^2 E}{dz^2} + \left[ n(z)k_0 \right]^2 E = 0 \]  \hspace{1cm} (2.4)

If we neglect the terms containing \( (\Delta n)^2 \) and use \( \beta = n_{\text{eff}} k_0 \) we have

\[ \left[ n(z)k_0 \right]^2 = \beta^2 + 4\beta \kappa \cos(2\beta_0 z) \]  \hspace{1cm} (2.5)

the element \( \kappa \) is called the coupling coefficient given by

\[ \kappa = \frac{\pi \Delta n}{2 \lambda} \]  \hspace{1cm} (2.6)

If we only consider wavelengths that are near to the Bragg wavelength \( \lambda_B \), then \( \beta = \beta_0 + \Delta \beta \) with \( \Delta \beta << \beta \). The electric field is the sum of the left and right propagating waves:

\[ E(z) = R(z) \exp(-i\beta_0 z) + S(z) \exp(i\beta_0 z) \]  \hspace{1cm} (2.7)

The functions \( R(z) \) and \( S(z) \) vary comparatively slowly with \( z \) because we have included the rapidly varying phase factor in the exponential functions. Inserting 2.5
and 2.7 into 2.4 and neglecting second derivatives, as these are much smaller than the first derivatives, a pair of coupled-mode equations are derived

\[
\frac{dR}{dz} = i\Delta\beta R = -i\kappa S \tag{2.8}
\]

\[
\frac{dS}{dz} = -i\Delta\beta S = i\kappa R \tag{2.9}
\]

Considering the case of figure 2.1 below which is a periodic grating in which the index varies in a stepwise manner between two values and where each subsection of the structure has a length of half a period, from the Fresnel formula the reflection coefficient \( r \) from the first discontinuity is

\[
r = \frac{\Delta n'}{2n'_{\text{eff}}} \tag{2.10}
\]

![Figure 2.1. Propagation and reflection in a “square” grating.](image)

The field reflection from the next discontinuity is \(-r\) as we are going from a high to low refractive index. When the wavelength is equal to the Bragg wavelength, the phase change for a round trip in a subsection is \( \beta_0\Delta = \pi \), corresponding to a factor of \(-1\). Therefore the reflections all add up in phase and the reflectivity per unit length (with two reflections per period) is
\[ \kappa' = \frac{2r}{\Lambda} = \frac{\Delta n}{n_{\text{eff}}} \frac{2n_{\text{eff}}}{\lambda_B} = \frac{2\Delta n}{\lambda_B} \]  

(2.11)

Therefore the coupling coefficient \( \kappa \) can be described as the amount of reflection per unit length. The coupled mode equations together with equation 2.7 describe the field in a structure with a periodic index. If we know \( R \) and \( S \) at a given point we can find it at any other point and we can write the general solution as

\[ R(z) = \left[ \cosh(\gamma z) - \frac{i \Delta \beta}{\gamma} \sinh(\gamma z) \right] R(0) - \frac{i \kappa}{\gamma} \sinh(\gamma z) S(0) \]  

(2.12)

\[ S(z) = \frac{i \kappa}{\gamma} \sinh(\gamma z) R(0) + \left[ \cosh(\gamma z) + \frac{i \Delta \beta}{\gamma} \sinh(\gamma z) \right] S(0) \]  

(2.13)

where

\[ \gamma^2 = \kappa^2 - \Delta \beta^2 \]  

(2.14)

Introducing the length \( L \) for distance \( z \)

\[ R(L) = \left[ \cosh(\gamma L) - \frac{i \Delta \beta}{\gamma} \sinh(\gamma L) \right] R(0) - \frac{i \kappa}{\gamma} \sinh(\gamma L) S(0) \]  

(2.15)

\[ S(L) = \frac{i \kappa}{\gamma} \sinh(\gamma L) R(0) + \left[ \cosh(\gamma L) + \frac{i \Delta \beta}{\gamma} \sinh(\gamma L) \right] S(0) \]  

(2.16)

We can write this in matrix form as:

\[
\begin{bmatrix}
R(L) \\
S(L)
\end{bmatrix} = F_{\text{per}}(L) \begin{bmatrix}
R(0) \\
S(0)
\end{bmatrix}
\]  

(2.17)

This is a transfer matrix that relates the right and left propagating waves at one end of the structure to the right and left propagating waves at the other end of the structure. Using a periodic structure of length \( L \) and having \( S(0) = 0 \) the field reflection coefficients are
Therefore if $\kappa L$ is very close to $\Delta \beta L$, $\gamma L$ is small, and we get to the first order:

$$ r_{\text{per}} \approx \frac{-i\kappa L}{1 + i\Delta \beta L} $$

(2.19)

Therefore $r_{\text{per}}$ increases with increasing $\kappa L$ (a higher coupling coefficient leads to a stronger reflection), $r_{\text{per}}$ decreases with increasing $\Delta \beta L$ (the reflection becomes smaller when the wavelength deviates from the Bragg wavelength). This is the basics of two of the most successfully manufactured single mode lasers, the distributed Bragg reflector laser (DBR) and the distributed feedback laser (DFB).

**Distributed Bragg Reflector Lasers**

For wavelengths close to the Bragg wavelength the reflections from individual parts of the grating are in phase and the reflection coefficients are high, and similarly far from the Bragg wavelength the reflections will be low. This wavelength dependence of the reflection can be used to achieve a wavelength dependent cavity gain for a laser by using a periodic structure as a reflector at one or both ends of the laser i.e. a distributed Bragg Reflector (DBR) laser. We can define the coupling strength as the product of the coupling coefficient $\kappa$ and the laser length $L$, and the deviation from the Bragg wavelength by the dimensionless product $\Delta \beta L$. The deviation $\Delta \lambda$ of the wavelength $\lambda$ from the Bragg wavelength $\lambda_B$ is related to the deviation of the propagation consent $\beta$ from the Bragg propagation constant $\beta_0$.

$$ \Delta \beta = \beta - \beta_0 = \frac{2\pi n_{\text{eff}}'(\lambda)}{\lambda} - \frac{2\pi n_{\text{eff}}'(\lambda_B)}{\lambda_B} \approx \frac{2\pi n_g}{\lambda_B^2} \Delta \lambda $$

(2.20)

At the Bragg wavelength with a periodic structure of length $L$ as a reflector for an incoming wave with an amplitude $R(0)$ at $z = 0$, and no incoming wave and no reflection at $z = L$ that is $S(L) = 0$, the solutions of 2.15 and 2.16 are
\[ R(z) = \frac{\cosh[\kappa(z - L)]}{\cosh(zL)} R(0) \quad (2.21) \]

\[ S(z) = \frac{i \sinh[\kappa(z - L)]}{\cosh(zL)} R(0) \quad (2.22) \]

At the Bragg wavelength the magnitude and field of the power reflection coefficient only depend on \( \kappa L \) as

\[ |r_{\text{per}}| = \tanh(\kappa L) \quad (2.23) \]

\[ R_{\text{per}} = |r_{\text{per}}|^2 = \tanh^2(\kappa L) \quad (2.24) \]

With a value of \( \kappa L \) of more than about 0.7 gives reflectivity similar or higher than cleaved facets. For wavelengths away from the Bragg wavelength, the power reflectivity can be derived from equation 2.18. The reflection bandwidth \( \Delta \lambda_r \) is found using 2.20 and approximating \( \Delta \beta = 2\kappa \)

\[ \Delta \lambda_r = \frac{\lambda_B^2 \kappa}{\pi n_{g, \text{eff}}} = \frac{\lambda_B \Delta n}{2 n_{g, \text{eff}}} \quad (2.25) \]

Here this grating idea is extended to include periodic grating with a variation on the refractive index in the x or y directions also. If we have a first order rectangular grating with equal lengths of mark and space regions (figure 2.2) then

\[ \kappa = \frac{2 \Delta n_{\text{eff}}}{\lambda_B} = \frac{2(n_{\text{eff}, A} - n_{\text{eff}, B})}{\lambda_B} \quad (2.26) \]

Figure 2.2. Grating Structure; A and B indicate "mark" and "space" regions.
Considering the presence of the grating as a perturbation, then from the wave equation

\[
\Delta n_{\text{eff}}' = \Gamma (n_1 - n_2)
\]  

(2.27)

where \( \Gamma \) is the confinement factor for the grating of thickness \( d_g \). The first order grating with equal mark and space periods is one that gives the highest coupling coefficient. For other grating shapes we can write the coupling coefficients as

\[
\kappa = \left( \frac{2\Delta n_{\text{eff}}'}{\lambda_B} \right) f_{\text{red}}
\]  

(2.28)

where \( f_{\text{red}} < 1 \) is a reduction factor. For a rectangular grating with unequal length of the mark and space regions the reduction factor follows from the Fourier coefficient of the grating shape

\[
f_{\text{red}} = \sin \left( \pi \frac{\Lambda_m}{\Lambda} \right)
\]  

(2.29)

where \( \Lambda \) is the mark extent and \( \Lambda \) is the total mark and space extent. This result can be extended to gratings of higher order with \( M \) denoting the order

\[
f_{\text{red}} = \frac{1}{M} \left| \sin \left( \pi \frac{\Lambda_m}{\Lambda} M \right) \right|
\]  

(2.30)

Figure 2.3 below shows the reduction factor \( (f_{\text{red}}) \) versus the relative mark length \( (\frac{\Lambda_m}{\Lambda}) \) for the first three grating orders.
Figure 2.3. The reduction factor ($f_{\text{red}}$) versus the relative mark length ($\frac{\Delta_m}{\Lambda}$) for the first three grating orders.

Considering the grating of order 2, $f_{\text{red}} = 0$ for a mark-to-period ratio of 0.5 because the two reflections from one period are in anti-phase. Second order gratings with mark-to-period ratios of 0.25 and 0.75 correspond to first order gratings with half the reflections missing, therefore $f_{\text{red}} = 0.5$.

**Two Section DBR Laser**

![Two Section DBR Laser](image)

Figure 2.4. Two section DBR laser showing the grating and active region.
The wavelength tunability of a DBR laser is dependent upon the injection current in the active region and mirror sections of the laser. Here this dependence is analysed by looking at a design to access 12 super modes spaced 50 GHz apart using a two section DBR laser as shown schematically in figure 2.4 above is analysed. The device specifications are given in [1]. For a device with one facet cleaved (R₁) and the other as a passive grating (R₂) we find the mirror loss from

$$\alpha_m = \frac{1}{L} \ln \left( \frac{1}{R_1 R_2} \right)$$  \hspace{1cm} (2.31)$$

where L is the overall laser cavity length and equals

$$\frac{c}{2 < n_g > \Delta f} = 750 \mu m$$  \hspace{1cm} (2.32)$$

taking \( <n_g> \) as the average effective group index and \( \Delta f \) as the required frequency change. The threshold gain \( g_{th} \) can be found from

$$\Gamma g_{th} = \alpha_i + \alpha_m$$  \hspace{1cm} (2.33)$$

where \( \Gamma \) is the product of the lateral and transverse confinement factors and \( \alpha_i \) is the internal loss. The power out of the cleaved end is

$$P_{01} = \eta_{d1} \frac{h \nu}{q} (I - I_{th})$$  \hspace{1cm} (2.34)$$

with \( \eta_{d1} \) the differential efficiency of the cleaved end and is calculated from

$$\eta_{d1} = F_i \eta_i \frac{\alpha_m}{\Gamma g_{th}}$$  \hspace{1cm} (2.35)$$

where \( \eta_i \) is the internal quantum efficiency and \( F_i \) is the fraction of power out of the cleaved end. Neglecting non-radiative recombination which holds for low current injection regimes the carrier density is proportional to the square root of the grating current. Therefore the frequency shift due to a change in grating current is determined from
\[ \Delta f = f \frac{dn_g}{dN} \left[ \frac{n_l I_g}{qV} \right] \] (2.36)

where \( n_g \) is the group index, \( f \) is the frequency of the light, \( q \) is the electronic charge, \( V \) is the grating frequency which depends on the grating and \( I_g \) is the grating injection current. Figure 2.5 plots the output power versus active section injection current and figure 2.6 plots the frequency deviation versus grating injection current.

Figure 2.5. Output power versus active section injection current.
Distributed Feedback Lasers

In DBR lasers the active region which provides the gain and the Bragg mirror which provides the wavelength selectivity are separated in the longitudinal direction as depicted in figure 2.4. In distributed feedback lasers (DFB) both the Bragg grating and the active region are distributed along the laser cavity in the longitudinal direction, with the grating above the active region in an index coupled structure as depicted in figure 2.7 making these lasers easier to fabricate as there is no integration of active and passive sections required.
In DFB lasers the gain and phase conditions cannot be separated and the analysis is more complex than a DBR laser however, as the laser is essentially a single periodic structure we can analyse it using transfer matrix theory as in [1]. In analogy with DBR lasers in the previous section we represent the oscillation condition as

\[
\cosh(\gamma L) + \frac{j(\Delta \beta + jg_0)}{\gamma} \sinh(\gamma L) = 0
\]  

(2.37)

where we have added \(jg_0\) to allow for the presence of gain and \(\gamma\) is given by

\[
\gamma^2 = \kappa^2 - (\Delta \beta + jg_0)^2
\]  

(2.38)

where \(\kappa\) is the coupling coefficient from (2.29). (2.37) can be rewritten as

\[
\gamma L \coth(\gamma L) = -j(\Delta \beta L + jg_0 L)
\]  

(2.39)

Solving eqn (2.39) numerically for defined products of coupling strength (\(\kappa\)) and cavity length (\(L\)) gives possible values of \(\Delta \beta L\) and \(g_0 L\), which is shown in figure 2.8 below.

![Figure 2.8 DFB modes for differing \(\kappa L\).](image)

As shown above in figure 2.8 no DFB modes exist at \(\Delta \beta L = 0\) (therefore \(\Delta \beta = 0\), as \(L\) can never be 0), this means that there is no propagation at \(\Delta \beta = 0\) which is the Bragg...
wavelength. This is the DFB stop band and is analogous to the stop band in electronic structure in solid state physics. At this exact Bragg wavelength ($\Delta \beta = 0$)

$$\gamma^2 = \kappa^2 + g_0^2$$

(2.40)

And we see two modes at the same distance from the Bragg wavelength and hence single mode operation in this kind of DFB laser is not possible. To better understand this concept consider a rectangular grating as in figure 2.9.

![Standard DFB](image)

Figure 2.9 Schematic of standard DFB grating with reflectivity R, from [5]

For this grating, the cavity can be taken to be anywhere inside the DFB since all periods look the same, the active length ($La$) is therefore a quarter-wavelength long taking the mirror reference planes as in the figure above yielding a zero grating reflection phase at the Bragg wavelength and therefore this type of configuration is anti-resonant at the Bragg wavelength. Introducing a cavity a half-wavelength long as in [6, 7] the device becomes resonant at the Bragg frequency where the reflection phase is zero. This is termed a quarter-wave shifted DFB as a half wavelength mirror spacing corresponds to a quarter-wave shift between the two gratings as shown in figure 2.10 below.
Other methods to achieve single mode DFB lasers are to leave one or both facets cleaved rather than AR coating both as in [8]. Introducing the cleaving will destroy the degeneracy of the modes and allow one to reach threshold first as the net reflection phase from one end is shifted from that of the grating alone. However this will introduce a yield problem since the reflection from the cleave will have a random relative phase and the yield depends on the required end loss differences described in more detail in [9]. Gain coupled DFB lasers also have single mode operation possible as the refractive index difference across the cavity is purely imaginary for the case of added gain or loss. This occurs if the grating consists of sections of refractive index of \( n_1 \) and \( n_2 \). As the refractive index change \( (n) \) is imaginary for added gain or loss then \( n_2 = n_1 + in_i \). From Fresnel's equation \( r = in_i/(2n) \) therefore the net grating reflection at the Bragg wavelength is purely imaginary and lasing can occur at the Bragg wavelength.
Tuning Mechanisms

Current Injection Tuning

Continuous, Discontinuous and quasicontinuous tuning.

In this section an outline of the physics and types of tuning mechanisms by which a semiconductor laser diode may be controlled is given. A more in-depth analysis is found in [1]. For laser operation at a frequency \( v \) \((2.41)\) must be satisfied, \((2.42)\) follows directly from \((2.41)\) which shows the phase change must be a multiple of \( 2\pi \)
after each roundtrip.

\[
G(v) = r_1r_2 \exp(-2i\beta L) = 1 \tag{2.41}
\]

\[
\phi(v) = \frac{2\pi v}{c} 2\sum_i n_i L_i = 2\pi \tag{2.42}
\]

where \( G \) is the roundtrip cavity gain, \( \phi \) is the roundtrip phase, \( \beta \) is the complex propagation constant, \( r_1 \) and \( r_2 \) are the mirror power reflectivities and \( c \) is the speed of light. \((2.41)\) defines a set of discrete frequencies called the cavity (or longitudinal) modes. These cavity modes are the modes which require the least pumping of the laser to satisfy \((2.41)\). Figure 2.11 (a) shows a simplified equivalent circuit of a laser oscillator depicting the spontaneous emission, the cavity roundtrip gain and the phase-shifting function by the cavity transit time.

![Figure 2.11. a - Simplified equivalent circuit of a laser oscillator, b - wavelength dependent cavity roundtrip gain and phase shift.](image-url)
Figure 2.11(b) indicates that the dominant lasing mode is roughly defined by the peak in the cavity roundtrip gain. Inspecting figure 2.11(a) shows that tuning of the laser can be done by varying $G(v)$, the cavity roundtrip gain or by adjusting $\Phi(v)$, the phase shift, or both. There are three basic tuning schemes which depend on the type of tuning and the device structure. These are continuous, discontinuous and quasicontinuous tuning schemes and are shown in figure 2.12.

![Figure 2.12](image)

Figure 2.12. a - Continuous, b - Discontinuous and c - quasicontinuous tuning schemes

In the continuous tuning scheme, the laser wavelength is tuned smoothly in arbitrarily small steps and the same cavity mode is lasing throughout the entire tuning range. In the discontinuous tuning scheme, the tuning range is solely determined by the cavity gain which means that longitudinal mode hops are allowed and this provides a larger tuning range although it is impossible to access certain wavelengths inside the tuning range. In the quasicontinuous tuning scheme, we overlap continuous regions to get full wavelength coverage over a wider range by tuning the cavity mode and the loss minimum over a longitudinal mode spacing and then changing to the next cavity mode and again tuning over a longitudinal mode.
Tuning of the cavity gain, tuning of the comb mode and electronic control of tuning.

Tuning of the cavity gain can be done by producing a spectral shift of the cavity gain curve as shown in figure 2.13 below.

Figure 2.13. Wavelength tuning by shifting the gain peak wavelength.

In this tuning mechanism, the gain peak wavelength is shifted by either varying the wavelength dependence of the active medium gain or by using mirrors with a tunable wavelength-selective mirror loss. When $\Delta \lambda_p$ increases above $\Delta \lambda_N/2$ then a mode hop occurs and the mode at $\lambda_{N-1}$ starts to lase. Using this method the wavelengths in between the mode hops are not accessible and so this is the discontinuous tuning scheme. Tuning of the comb-mode spectrum is done by keeping $\lambda_p$ fixed and changing the optical length of the laser by adjusting which cavity mode is lasing. The difference in this method to the cavity gain method is that the mode wavelengths change linearly within each mode jump as illustrated in figure 2.14 b.

Figure 2.14. a - Wavelength tuning by shifting the comb-mode spectrum., b - Laser wavelength versus comb-mode shift.
In a simple Fabry-Pérot laser above threshold the gain clamping mechanism prevents significant carrier changes so that the variation of the semiconductor gain curve by changing the injection current has very little impact on the lasing wavelength. In the tunable lasers described in later chapters the gain is not completely clamped above threshold and, as such, continuous tuning of the laser is possible.

Electronic Wavelength control

In order to have control of the output wavelength of a tunable laser diode we need to control the position of the gain peak wavelength of the cavity round trip gain ($\lambda_p$) and/or the longitudinal modes ($\lambda_n$). The gain peak wavelength ($\lambda_p$) is dependent on the injected carrier density and in a simple Fabry-Pérot laser as stated above the carrier density clamps above threshold therefore there is little wavelength tuning in Fabry-Pérot laser diodes. Widely tunable laser diodes can rely on this mechanism for large wavelength tuning if there are un-clamped carrier density regions such as passive gratings.

Therefore in order to shift the output wavelength we need to change the positions of the longitudinal modes ($\lambda_n$) by changing the real part of the effective refractive index as seen in the phase condition below (2.43)

$$\lambda_n = \frac{2n'_{\text{eff}}(\lambda_i)L}{m}$$

(2.43)

where $n'_{\text{eff}}$ is the effective refractive index, $L$ is the cavity length and $m$ is the mode number. Therefore to control the output wavelength we need a waveguide with an electronically controllable effective refractive index where the amount of tuning is proportional to the product of the cavity length and the effective refractive index. With simple Fabry-Pérot laser diodes this provides little tuning of the output wavelength and so we look again at DBR and DFB type lasers. In DBR and DFB lasers the tuning of the cavity round-trip gain may be accomplished by tuning the Bragg reflector hence changing the position of the comb modes. Looking at equation (2.3) again
\[ \Lambda = \frac{\Lambda_B}{2n_{\text{eff}}} \]  

(2.44)

we see that the only element that can be changed is the effective refractive index as the grating element is fixed during the fabrication of the Bragg mirror. As the effective refractive index is determined by the confinement factor and the refractive index of the layers of the laser diode any changes in the refractive index in any of these layers can change the effective refractive index and therefore the end loss \( \alpha_m(\lambda) \). This type of tuning is employed commonly in many tunable laser diodes [13, 14].

The extent of the lasers continuous tuning when the same cavity mode lases across the wavelength span can be determined easily from (2.45)

\[ \frac{\Delta \lambda}{\lambda_0} = \frac{|\Delta n_{\text{eff}}|}{n_{g,\text{eff}}} \]  

(2.45)

where \( \Delta \lambda \) is the wavelength tuning, \( \lambda_0 \) is the Bragg wavelength \( \Delta n_{\text{eff}} \) is the change in the real part of the effective refractive index and \( n_{g,\text{eff}} \) is the group effective refractive index. Allowing for mode hops between different longitudinal modes (discontinuous tuning) then the maximum tuning width is dependent on the spectral width of the gain envelope function. From this analysis we see that the electronic control of the wavelength of a tunable laser diode is dependent on our ability to control the effective refractive index of the laser. The effective refractive index may be controlled in practice by three different methods either carrier induced effects (free carrier plasma effect), by applying an electric across the device (quantum confined Stark effect) or by varying the temperature of the device (thermal tuning).

**Free carrier plasma effect**

The free carrier plasma effect is the most widely used mechanism to tune semiconductor laser diodes and has achieved the largest tuning ranges [1]. The free carrier plasma effect works mainly by changing the refractive index due to the injection of an electron-hole plasma into the semiconductor. This electron-hole plasma polarizes the free carriers and also spectrally shifts the absorption edge of the semiconductor [10, 11]. The polarization effect is much larger than the absorption edge shift in the case of a passive wavelength control waveguide section when the
bandgap energy is larger than the photon energy. The refractive index change due to a change for an carrier injection is given in (2.46) below.

\[
\Delta n' = -\frac{e^2 \lambda^2}{8\pi^2 c^2 n \varepsilon_0} \left( \frac{1}{m_e} + \frac{1}{m_h} \right) N
\]  

(2.46)

where \( c \) is the speed of light, \( n \) is the refractive index, \( \varepsilon_0 \) is the free space permittivity, \( m_e \) is the electron effective mass, \( m_h \) is the hole effective mass and \( N \) is the injected carrier density. This implies a negative refractive index change and therefore a negative wavelength change i.e. a blue-shift. There is also a change in the optical gain due to the change in the imaginary part of the refractive index which is given by

\[
2k_0 \Delta n'' = -\frac{e^3 \lambda^2}{4\pi^2 c^3 n \varepsilon_0} \left( \frac{1}{m_e^2 \mu_e} + \frac{1}{m_h^2 \mu_h} \right) N
\]  

(2.47)

where \( \mu_e \) is the electron mobility and \( \mu_h \) is the hole mobility. Also the injection of carriers causes band filling and band gap shrinkage which have a refractive index change of the same sign as the polarization effect and therefore increase the index change with injected carriers. These are the main effects by which the tunable lasers are tuned in this work.

**Quantum-confined Stark effect**

The quantum confined Stark effect also called the electro-optic effect is weak in usual III-V semiconductor lasers however the effect is stronger in multiple quantum well lasers and is observed by placing the quantum wells in an electric field that reduces the bandgap energy by effectively making the band edges inclined relative to each other, thereby reducing the energy between the lowest order wavefunction of the conduction band and the lowest order wavefunction in the valence band as depicted in figure 2.15 below.
Typically the effect is still very small (refractive index changes of $10^{-3}$ to $10^{-2}$) even in multiple quantum well lasers where the quantum well used in the tuning section matches the laser wavelength [12, 13], however with asymmetric quantum wells the refractive change can be increased to $\sim 0.01$ as in [14, 15]. As the quantum confined Stark effect is not used in this project to achieve tuning of laser diodes it will not be discussed further.

**Thermal Tuning**

The lasing wavelength of a semiconductor laser diode is very dependent on the temperature of the diode as both the bandgap energy and the refractive index change with temperature, the cavity length also change due to thermal expansion however this is a small change over temperatures ranges that we deal with ($\Delta T \sim 50^\circ$C). From [1] if we assume that we supply a current $I = 30$ mA, with a device resistance of $R = 4 \Omega$ and photon energy of 0.8 eV ($\sim 1550$ nm), we find that a total of 19.6 mW of power supplied to the laser is lost giving a temperature increase of around 2 K. Due to the thermal dependence of the bandgap energy we see a thermal dependence of the gain curve and therefore the peak gain wavelength. The dependence of $\lambda_p$ on the temperature gives Fabry-Pérot type lasers their typical peak gain wavelength temperature dependence of 0.5 nm/K which corresponds to $-2.5 \times 10^{-4}$ eV/K. Due to the temperature dependence of the refractive index the cavity modes and therefore the above threshold lasing mode will tune as 0.1 nm/K. For DFB and DBR lasers the lasing wavelength is determined by the Bragg grating and so a temperature change can result in a mode hops. However any heating of the laser cavity will also increase
the threshold current and decrease the differential efficiency (the change in output power per unit change in drive current) of the laser diode. This can limit the tunability of a laser diode by temperature tuning. In wavelength tunable laser diodes increasing the drive current will increase the temperature which as stated above increases the refractive index however the carrier effects will decrease the refractive index and this leads to a limitation in refractive index wavelength tuning.

A comparison of the above mentioned techniques for tunable laser diodes are shown in table 2.1 below from [1]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plasma Effect</th>
<th>Quantum confined Stark effect</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>An</td>
<td>-0.04</td>
<td>-0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>T</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Aλ</td>
<td>-8 nm</td>
<td>-1 nm</td>
<td>+5 nm</td>
</tr>
<tr>
<td>aH</td>
<td>-20</td>
<td>-10</td>
<td>large</td>
</tr>
<tr>
<td>Heat generation</td>
<td>large</td>
<td>negligible</td>
<td>very large</td>
</tr>
<tr>
<td>Technology</td>
<td>moderate</td>
<td>demanding</td>
<td>simple</td>
</tr>
</tbody>
</table>

Table 2.1. Tuning mechanisms for semiconductor laser diodes.

where Δn is the refractive index change, T is the change in the optical confinement in the active region of the device, Δλ is the output wavelength change, aH is the change in the linewidth enhancement factor, heat generation is the amount of heat generated in the device and technology refers to the difficulty in fabrication of the device.

**Vernier Effect Tuning**

We have already seen how DBR and DFB type laser diodes can be tuned by either changing the injected current or changing the temperature, however there is a limit to the tunability achieved by these methods (5-10 nm) due to a limit in how much the refractive index can be changed. The gain bandwidth available to multiple quantum well lasers is ~ 100 nm and Erbium Doped Fibre Amplifiers (EDFA) have access to ~ 40 nm in the C or L band. Therefore there has been a large amount of research in extending the tunability of laser diodes beyond the refractive index limit [16-26].

Increases in tunability can be obtained by using coupled cavities or array waveguide lasers which are discussed below however these induce large complexities into the laser design and growth. In order to increase the tunability further we use a technique
that allows us to use the change in the refractive index difference instead of the refractive index itself, therefore allowing a relative wavelength change to be used which can be much larger than the wavelength change due to a refractive index change. One method that exploits this relative refractive index difference of semiconductor lasers is the Vernier effect. This effect requires two differing wavelength dependent mirror reflectivities to produce two spectrally different comb mode reflection spectra. The comb mode reflection spectra peaks will overlap at certain wavelengths which are the wavelengths where lasing will occur as the gain will overcome loss since the round-trip loss is inversely proportional to the product of both mirror reflectivities. Both mirror reflection spectra can be directly and independently controlled by controlling the effective refractive index in these mirror regions. Any change in the effective refractive index in the mirror regions will produce a shift in the comb mode reflection spectra and allow different reflection peaks to overlap shifting the wavelength accordingly. This idea of Vernier tuning the output wavelength is shown in figure 2.16. This method can greatly increase the tuning range and lasers such as the Sample Grating Distributed Bragg Reflector (SGDBR) laser which makes use of the Vernier tuning scheme have recorded tuning ranges of 60 nm [27], however some limitation apply to this kind of tuning which are:

- If two modes are overlapped and on the gain curve some other means of suppressing the unwanted mode must be employed to preserve a high SMSR.
- There must be large enough cavity gain to suppress other competing modes.
- To achieve continuous tuning there must be a phase control element meaning that the round trip phase must be a multiple of $2\pi$. 
SGDBR laser

The sample grated distributed Bragg reflector (SGDBR) is one laser that makes use of the Vernier effect between both of its mirror reflection spectra to tune over large wavelength ranges. The comb like mirror reflection spectra are achieved by using a sample grating which consists of several layers of interrupted grating with a sampling period of $L_s$ which is equivalent to a short cavity, a schematic of the grating is shown in figure 2.17 below.

\[ \Delta \lambda_s = \frac{\lambda^2}{2n_g L_s} \]  

(2.48)

where $n_g$ is the group refractive index. By controlling the refractive index of both mirrors separately and having differing sampling lengths in each mirror section the
wavelength output can be controlled using the Vernier tuning mechanism described above. An SGDBR laser also employs a phase tuning section to allow for quasi-continuous tuning across the wavelength range of interest. A schematic of an SGDBR laser is shown in figure 2.18 below.

![Figure 2.18. A schematic of an SDDBR laser diode.](image)

A typical SGDBR wavelength map is shown in figure 2.19 below.

![Figure 2.19. Wavelength versus front and back section injection currents for an SGDBR laser diode.](image)

Additional details on the SGDBR can be found in [1, 16, 28, 29].
External-Cavity Laser

Although many types of tunable lasers exist one of the most commonly used for characterisation purposes is the external cavity laser (ECL) where the wavelength selection and tuning functions are external to the semiconductor structure providing the amplifying medium. For these lasers to operate effectively an anti-reflecting (AR) coating must be applied to the facet which is closest to the external cavity as outlined in figure 2.20 below.

The first diffracted order feedback occurs for wavelength $\lambda$ when

$$\lambda = 2\Lambda \sin(\theta)$$

(2.49)

where $\Lambda$ is the period of the grating and $\theta$ is the incident angle on the grating from figure 2.20. As the linewidth is inversely dependent on the number of photons in the laser cavity and proportional to the spontaneous emission rate, it is then proportional to the inverse square of the external cavity length, assuming that the length of the external cavity is much larger than the internal cavity. This can lead to a very narrow linewidth of the order of a few kilohertz. From (2.49) by rotating the grating the output wavelength can be varied in a discontinuous tuning fashion with mode hops between wavelengths. For continuous tuning the grating is rotated and the external cavity length is varied simultaneously, this can be achieved if the grating is pivoted on a point below or above the collimating lens in figure 2.20 [1]. An alternative is the Littman-Metcalf configuration [30] in which there is a fixed grating but an extra mirror is inserted which can be rotated. Experimentally obtained results for external cavity lasers are:

- 35 nm tuning @ 850 nm with output at 1 W [31]
• 55 nm tuning @ 1550 nm with 10-kHz linewidth [32]
• 105 nm tuning @ 800 nm [33]
• 242 nm tuning @ 1450 nm [34]

Further options include adding temperature tuned optical filters, electrooptically tunable birefringent filters or acoustooptic filters to provide wavelength tunability. 50 nm tuning range with SMSR over 40 dB from temperature tuned optical filter external cavity laser [35], 7 nm tuning range with a linewidth under 60 kHz has been reported for the birefringent filter [36] and 83 nm tuning has been reported for the acoustooptic filter [37].

The main drawback of external cavity lasers is maintaining their mechanical and thermal stability to avoid mode hops due to changes in the external cavity length. This can be achieved by having more compact lasers by making use of micro electro-mechanical structures (MEMS). MEMS improves the overall stability of these devices and has been shown to achieve 40 nm tuning with SMSR of over 55 dB [38]. This type of tunable laser is used extensively throughout this project and in particular in chapter 4 to characterise the waveguide loss.

Vertical-Cavity Lasers

Vertical cavity surface emitting lasers (VCSELs) are a vertical semiconductor laser in which the lasing is perpendicular to the plane defined by the active region as in figure 2.21 and are used extensively for short reach data communications.

![Figure 2.21. Schematic of VCSEL](image-url)
These lasers have no cleaved facets but instead rely on feedback provided by the DBR mirror pairs. Due to their very short cavity length the longitudinal mode spacing is large and as such single mode operation is possible with no other wavelength selective elements. The most common method to tune a VCSEL is by thermally tuning the Distributed Bragg Reflector (DBR) mirror. By using thin film heaters a continuous tuning range of 10 nm has been observed [39]. However thermal tuning is slow and requires a large temperature change. Other methods to tune VCSELs include mounting an external mirror and using MEMS technology to create a mini external cavity VCSEL device. A tuning range of 19 nm is recorded with a threshold current of 0.5 mA in [40].

**Laser Arrays**

Laser arrays are arrays where multiple lasers operate at slightly different output wavelength and can have spatially differing outputs or combined together to form one output. Two kinds of laser arrays are described here DBR arrays and Phase arrays.

**DBR laser arrays**

In a DBR laser array multiple DBR lasers with tuning ranges larger than the wavelength spacing between DBR lasers are combined together to provide larger tuning ranges than single DBR lasers. DBR laser arrays without an integrated combiner have been shown to have an overall tuning of 27 nm with 4 laser elements in [41]. DBR laser arrays with an integrated combiner and an amplifier to compensate for coupling losses have been described in [42]. The tuning range of a 4 DBR laser array coupled with Y couplers are described in [43] and show a tuning of 21 nm with switching speed of 4 ns.

**Phased Arrays**

Figure 2.22 shows an array waveguide laser where the different lengths of the curved waveguides cause different wavelengths to be coupled into difference output waveguides. Phased array waveguides lasers have been shown to have an overall of 26 nm discontinuous tuning in [44] with 16 channels and each channel can be thermally tuned to provide complete continuous tuning over this range.
Figure 2.22. Phased array laser waveguide.
References


Chapter 3 – TMM and SMM Theory

Scattering and Transfer matrix methods
Here the scattering matrix method (SMM) and transfer matrix method (TMM) is presented to analyse Fabry-Pérot (FP) lasers which can be extended to analyse laser diodes with internal dielectric interfaces as will be described in chapter 5. A good introduction is to be found in [1]. In the following the normalised amplitude \(a_i\) is used which has a magnitude equal to the square root of the power flow, as this is more convenient when working with complex laser cavities. It is also convenient to reference the phase to the electric field which is given by (3.1)

\[
E(x, y, z, t) = \hat{e}E_0 U(x, y)\exp\left(i(\omega t - \beta z)\right)
\] (3.1)

where \(\hat{e}\) is the unit vector, \(E_0\) is the field magnitude, \(U(x, y)\) is the normalised electric field profile, \(\omega\) is the angular frequency, \(t\) is the time, \(\beta\) is the complex propagation constant and \(z\) is the propagation distance, then the normalised amplitude can be defined as

\[
a_j = \frac{E_0}{\sqrt{2\eta_j}} \exp\left(-i\beta z\right)
\] (3.2)

where \(\eta_i = 377\Omega/n_i\) is the mode impedance i.e. the ratio of the transverse electric to transverse magnetic field magnitudes of the mode. Therefore if \(\int |U|^2 dx dy = 1\) then \(a_j^* a_j = P_j\), the power is flowing in the positive \(z\)-direction. At waveguide reference planes there can be incident (input) and reflected (output) powers, we define the inputs as having normalised amplitudes \(a_j\) and the outputs as having normalised amplitudes \(b_j\). Therefore at port \(j\) the net power flowing into the port is

\[
P_j = a_j a_j^* - b_j b_j^*
\] (3.3)

By relating the outputs to the inputs linearly, the outputs can be expressed as a weighted combination of the inputs in a matrix form as
\[ b_i = \sum_j S_{ij} a_j \]  
(3.4)

where \( S_{ij} \) are called the scattering coefficients. To determine a particular \( S_{ij} \) all inputs except \( a_j \) must be set to zero, i.e.

\[ S_{ij} = \left. \frac{b_i}{a_j} \right|_{a_k = 0, k \neq j} \]  
(3.5)

and taking a more general view

\[ b = Sa \]  
(3.6)

where \( b \) and \( a \) are column vectors and \( S \) is a matrix. The two port scattering junction shown in figure 3.1 is given as an example in (3.7)

\[ \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \]  
(3.7)

where the \( S \) values are called scattering coefficients. These have direct physical significance where they represent the ratio of the normalised output amplitudes to normalised input amplitudes. For the example above \( S_{11} \) and \( S_{22} \) are simply \( r_1 \) and \( r_2 \) which are the amplitude reflectivities at junction 1 and 2. The power reflection coefficients are just \( |S_{11}|^2 \) and \( |S_{22}|^2 \). The off-diagonal terms are the complex (amplitude and phase) outputs at one port due to inputs at the other. The magnitude squared of these off diagonal elements ( \( |S_{ij}|^2 \) ) is the fraction of power appearing at the port \( i \) due to the power entering port \( j \). For a loss-less two port network, power
conservation yields, $|S_{11}|^2 + |S_{21}|^2 = 1$ and $|S_{22}|^2 + |S_{12}|^2 = 1$. Loss can be included by making these equalities less than 1.

The transmission matrix method (TMM) is used for cascading networks together as simple matrix multiplication can be used. The TMM expresses the inputs and outputs at a given port in terms of those at others, however here instead of using the input and output amplitudes ($a_i$ and $b_i$), we use the forward and backward travelling waves ($A_i$ and $B_i$) as shown in figure 3.2

![Figure 3.2. Transmission matrix representation of a two port network.](image)

where the transfer matrix (TM) is described as

$$
\begin{bmatrix}
A_1 \\
B_1
\end{bmatrix} =
\begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix}
\begin{bmatrix}
A_2 \\
B_2
\end{bmatrix}
$$

(3.8)

The correspondence between the transfer and scattering matrix representations is as follows: $A_1 = a_1$, $B_1 = b_1$, $A_2 = b_2$, $B_2 = a_2$. Therefore using the TMM a series of two port junctions can be multiplied together using matrix multiplication. This is illustrated by figure 3.3 below

![Figure 3.3 TM representation for two networks cascaded together.](image)

By setting $A_2 = A'_1$ and $B_2 = B'_1$ the field on the left can be related to the field on the right by

$$
\begin{bmatrix}
A_1 \\
B_1
\end{bmatrix} =
\begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix}
\begin{bmatrix}
A_2 \\
B_2
\end{bmatrix} =
\begin{bmatrix}
T'_{11} & T'_{12} \\
T'_{21} & T'_{22}
\end{bmatrix}
\begin{bmatrix}
A'_2 \\
B'_2
\end{bmatrix}
$$

(3.9)
Using this method the TM can be calculated for complex waveguide structures by matrix multiplication. The structures analysed in this thesis can be modelled equally using the TMM or the SMM. However if the models are extended in the future to include leaky modes which decay quickly with propagation distance then the SMM is a more stable algorithm due to numerical instabilities in the TMM when such modes are analysed. Detailed comparisons of both methods are shown in [2]. As the TMM and SMM can be used equally well here, I have chosen to use SMM throughout this thesis and the basics are given below.

**The dielectric interface**

A dielectric interface is characterised by having different refractive indices on each side of the interface. This is illustrated in figure 3.4 below.

The reference plane is placed at the physical boundary between the two areas of differing refractive indices giving the scattering junction a length of zero. From 3.5

\[
S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} = -r_1 = \frac{n_1 - n_2}{n_1 + n_2} \tag{3.10}
\]

where the reflection is positive if \( n_2 > n_1 \). \( S_{22} \) is found similarly

\[
S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0} = r_2 = -(-r_1) \tag{3.11}
\]

and
here the waves are assumed to be plane waves and have no loss at the interface as the interface has zero length and for waveguide modes power conservation suggests that the mode profiles are continuous across the dielectric interface. In real laser diodes scattering loss is included so that (3.12) is no longer valid. For this simple dielectric interface the scattering matrix is

$$S = \begin{bmatrix} -r_1 & t \\ t & r_1 \end{bmatrix}$$  \hspace{1cm} (3.13)$$

**Waveguide with no discontinuities**

In order to relate one side of a waveguide to the other along the propagation direction we need to know how to deal with a waveguide with no discontinuities as shown in figure 3.5.

This is just a length of waveguide, $L$ where we wish to relate the variable at $L$ to those at $0$. As there is no coupling between the forward and backward propagating waves, then $S_{11} = S_{22} = 0$, therefore

$$b_2 = a_1(L) = a_1(0)\exp(-i\beta L) = a_1 \exp(-i\beta L)$$  \hspace{1cm} (3.14)$$
\[ a_2 = b_1(L) = b_1(0) \exp(i\tilde{\beta}L) = b_1 \exp(i\tilde{\beta}L) \] (3.15)

Therefore the scattering matrix consists of the following scattering coefficients

\[
S = \begin{bmatrix}
0 & e^{-i\tilde{\beta}L} \\
e^{i\tilde{\beta}L} & 0
\end{bmatrix}
\] (3.16)

as from (3.5),

\[
S_{12} = \frac{b_1}{a_2} = \frac{a_2}{e^{i\tilde{\beta}L} a_2} = \frac{1}{e^{i\tilde{\beta}L}} = e^{-i\tilde{\beta}L}
\] (3.17)

where \( S_{21} \) is found in a similar fashion.

The modes undergo a phase shift of \(-\beta_reL\) over a distance \(L\) and a gain/loss rate \(\beta_i L\), where \(\beta_re\) is the real part of the complex propagation constant and \(\beta_i\) is the imaginary part, where \(\tilde{\beta} = \beta_re + i\beta_i\).

**Fabry-Pérot etalon**

Putting both structures described above together with another dielectric interface gives a dielectric segment which is called a Fabry-Pérot etalon (FPE). This structure is shown below in figure 3.6.

![Figure 3.6. Fabry-Pérot etalon.](image-url)
Usually for a FPE $n_1$ and $n_3$ are the same and $n_2 > n_1$ therefore $r_1$ and $r_2$ are positive real numbers. To determine the scattering matrix elements for a FPE the following procedure is adopted. From figure 3.6 the following relations are seen to be true.

\[ b_1 = -a_1 r_1 + a_1' t_1 \]  
\[ b_1' = a_1 t_1 + a_1' r_1 \]  
\[ b_2 = a_2 t_2 \]  
\[ b_2' = a_2' r_2 \]  
\[ a_1' = b_2' e^{-i\beta L} \]  
\[ a_2' = b_1' e^{-i\beta L} \]  
\[ a_1 = b_1 a_1' \]  
\[ b_2 = b_2 a_2' \]

Therefore solving for $S_{11} = b_1/a_1$ and $S_{21} = b_2/a_1$ while $a_2 = 0$ gives the following scattering matrix elements

\[ S_{11} = -r_1 + \frac{t_1^2 r_2 e^{-2i\beta L}}{1 - r_1 r_2 e^{-2i\beta L}} \]  
\[ S_{21} = \frac{t_1 t_2 e^{-i\beta L}}{1 - r_1 r_2 e^{-2i\beta L}} \]  
\[ S_{22} = -r_2 + \frac{t_2^2 r_1 e^{-2i\beta L}}{1 - r_1 r_2 e^{-2i\beta L}} \]  
\[ S_{12} = S_{21} \]

In these equations the common factor in the denominator gives rise to the Fabry-Pérot resonances.

The absolute squares of $S_{11}$ and $S_{21}$ gives the amount of power reflected and transmitted through the FPE as a function of wavelength. The loss at the interfaces is
taken to be zero in the following example and the amplitude reflection is assumed to be from a cleaved facet \((r = 0.55)\) therefore the amplitude transmission is 0.84 \((\text{as } t = \sqrt{1 - r^2})\). The complex propagation constant is determined from the gain and wavelength as
\[
\vec{\beta} = \beta_{re} + i\beta_i
\]
where \(\beta_{re} = \frac{2\pi n'}{\lambda}\) (3.28)

The magnitude reflection and magnitude transmission are shown in figure 3.7 and figure 3.8 below in the absence of any optical gain or loss across the cavity and with no loss at the dielectric interfaces. Three different mirror reflectivities are plotted with the amplitude reflectivity \(|r_1| = |r_2| = 0.2, 0.4 \text{ and } 0.6\). The phase of the reflection and amplitude is given by \(<S_{12}\) and the phase of the transmission is given by \(<S_{21}\), these are plotted versus wavelength and are shown in figures 3.9 and 3.10 respectively.

where \(n'\) is the real part of the complex refractive index and \(\lambda\) is the wavelength and

\[
i\beta_i = ik_0n'' = \frac{G}{2}
\]

(3.29)

where \(k_0\) is the free space propagation constant \((k_0 = 2\pi/\lambda)\) where \(\lambda\) is the wavelength, \(n''\) is the imaginary part of the complex refractive index and \(g\) is the optical gain/loss term. The gain/loss term refers to the optical gain or optical loss and is independent of any losses associated with the dielectric interfaces in any SMM calculations as these are contained in the relationship between the amplitude reflection and amplitude transmission.
Figure 3.7. Magnitude reflection versus wavelength for a Fabry-Pérot laser using the SMM method.

Figure 3.8. Magnitude Transmission versus wavelength for a Fabry-Pérot laser using the SMM method.
Figure 3.9. Phase of the reflection versus wavelength for a Fabry-Pérot laser using the SMM method.

Figure 3.10. Phase of the transmission versus wavelength for a Fabry-Pérot laser using the SMM method.
The output power out of one facet ($P_{01}$) relative to the power out of the other ($P_{02}$) is found from (3.30) evaluated at threshold for lossless mirrors

$$\frac{P_{01}}{P_{02}} = \left| \frac{S_{11}}{S_{21}} \right|^2$$

(3.30)

If we include mirrors with loss i.e. $t \neq \sqrt{1 - r^2}$ then the fraction of power ($F_1$) out of one facet ($P_{01}$) compared to the total power out of both the facets ($P_m = P_{01} + P_{02}$) is

$$F_1 = \frac{P_{01}}{P_m} = \frac{|b_1|^2}{|a_1|^2(1 - r_1^2) + |a_2|^2(1 - r_2^2)} = \frac{r_1^2}{(1 - r_1^2) + r_2^2(1 - r_2^2)}$$

(3.31)

and from [1, 3, 4] the external differential quantum efficiency ($\eta_d$) for light delivered out of a Fabry-Pérot laser can be described as

$$\eta_d = F_1 \eta_i \frac{\alpha_m}{\langle \alpha_i \rangle + \alpha_m}$$

(3.32)

where $\eta_i$ is the internal differential quantum efficiency, $\langle \alpha_i \rangle$ is the internal optical loss and $\alpha_m$ is the mirror loss (the facet loss). Therefore the power out of one facet ($P_{01}$)

$$P_{01} = \eta_{d1} \frac{h \nu}{q} (I - I_{th})$$

(3.33)

Figure 3.11 shows the mirror loss calculated for a Fabry-Pérot laser and figure 3.12 shows the calculated output power for the same laser, both these have experimentally determined optical gain curves from a 350 µm long Fabry-Pérot laser diode operating just under threshold.
In all the simulated results shown in this chapter the laser is 350 μm long with cleaved facets (power reflection 0.3), complex refractive index of 3.5. Figure 3.7 to figure 3.10 are simulated with no optical loss or gain, while figure 3.11 and 3.12 are simulated with an experimentally obtained FP laser net modal gain curve for a 350 μm long cavity with cleaved facets which is wavelength dependent.
Conclusion

The scattering matrix method introduced in this chapter will form the basics of the simulated results in the rest of this thesis. The scattering matrix method allows simple calculations for the dependency of the output wavelength on parameters such as the laser cavity and as such the interslot spacing which will be introduced in chapter 5.

References


Chapter 4 – Semiconductor Laser

Waveguides

Introduction to semiconductor waveguides

Semiconductor waveguides play a very important part in telecommunication systems. Semiconductor waveguides differ from optical fibres in that they conduct electricity and respond to external voltages therefore they are used extensively to propagate light between various optical components in a specific path. The characterisation of semiconductor waveguides is of high importance for the design of laser diodes built on various substrates. In this chapter the linewidth enhancement factor is introduced and calculated for two different material systems. Historically a smaller linewidth enhancement factor makes a better laser however for a tunable laser a larger linewidth enhancement factor may be better. The loss associated with waveguides is also determined by two different new methods. Here the waveguides are laser structures which are un-pumped. The loss is an important parameter for tunable slotted lasers as the slot introduces large losses into the cavity and so waveguide loss is important in designing tunable laser diodes. The last section in this chapter deals with spontaneous emission factor and internal quantum efficiency and ways to calculate these parameters.
Linewidth Enhancement Factor

Introduction to the Linewidth Enhancement Factor

In order to accurately model and produce high quality tunable laser diodes there is a need to optimise not only the laser design but also the material system used for the lasers. One of the parameters which must be known for a particular material system is the linewidth enhancement factor (alpha (α)). The α parameter is particularly important in characterising tunable lasers as it depends on the refractive index of the material system used to produce the laser. Here, this parameter is introduced from Maxwell’s equations and different methods are employed to measure it. The first is from the well known Hakki-Paoli (H-P) method from [1], the second method is the Fourier Transform (FT) method from [2], and the third is a new method that we have developed from a Fourier series expansion (FSE), which we have published in [3]. As an introduction to the linewidth enhancement factor a summary of Buus’s analysis in Chapter 2 section 2.2 [4] and Coldren’s analysis in [5] is briefly outlined here.

The average power per unit area of a uniform plane wave with field components \( E = (0, E_y, 0) \) and \( H = (H_x, 0, 0) \) propagating along the z-direction in an isotropic and non-magnetic medium is given by:

\[
I = \overline{E} \times \overline{H} = \frac{1}{2} \text{Re}\{E_y \cdot H_x^*\} \quad (4.1)
\]

which can be expanded using Maxwell’s equations as:

\[
I = \frac{cE_0}{2} n |E_0|^2 \exp\left(2k_0 n^{-} z\right) \quad (4.2)
\]

where \( c \) is the speed of light, \( \varepsilon_0 \) is the free-space permittivity, \( n^{-} \) is the real part of the refractive index, \( n^{-} \) is the imaginary part of the refractive index, \( E_0 \) is the amplitude at \( z = 0 \), \( k_0 \) is the free-space propagation constant (\( k_0 = 2\pi/\lambda \), where \( \lambda \) is the wavelength) and \( z \) is the distance along the z-axis. The optical gain \( g \), or loss \( \alpha \) is defined as:
\[ g = -\alpha = \frac{1}{l} \frac{dI}{dz} \] (4.3)

which is reduced to:

\[ g = 2k_0n'' \] (4.4)

From 4.3 and 4.4 we see that as the gain changes due to changes in the injected carrier density, the imaginary part of the refractive index also changes, therefore we may employ the Kramers-Kronig dispersion relation to calculate the changes of the real part of the refractive index from \( \Delta g \):

\[ \Delta n' (\omega) = \frac{c}{\pi} P \int_0^\infty \frac{\Delta g (\omega')}{\omega^2 - \omega'^2} d\omega' \] (4.5)

where \( P \) is the principle integral value.

As the laser will be lasing at the peak gain wavelength, these changes of the refractive index will produce ultra-fast frequency changes of the laser emission during relaxation processes. This will produce an enhancement of the laser spectral linewidth which is described by means of the linewidth enhancement factor \( (\alpha) \).

\[ \alpha = -\frac{\delta n' / \delta N}{\delta n'' / \delta N} = -\frac{4\pi}{\lambda} \frac{\delta n' / \delta N}{\delta g / \delta N} = -\frac{4\pi}{\lambda q} \frac{\delta n'}{\delta N} \] (4.6)

where \( q \) is used to define the differential gain. Due to this dependence, the linewidth is increased by a factor of \((1 + \alpha^2)\) as described by Cassidy in [6]. There are a number of important characteristics which depend on \( \alpha \), most notably the laser linewidth, but also the sensitivity to feedback, wavelength chirp and the gain guiding. The Hakki-Paoli method is the most common method of determining \( \alpha \). However, as the measured amplified spontaneous emission (ASE) spectra are the convolution of system response function with the intrinsic laser ASE spectra, this leads to a decrease of the peak intensities and an increase of the valley intensities in the measured spectra. Therefore, this method may underestimate the gain if the resolution bandwidth of the measurement system (optical spectrum analyser (OSA)) is not sufficient to resolve the peaks and valleys of the emission spectrum. Other methods to measure \( \alpha \) include the injection locking technique [7] and the Fourier transform method. The ASE is defined as the
spontaneous emission that has been optically amplified by the process of stimulated emission in a gain medium.

In the Fourier transform method, the entire ASE spectrum is Fourier transformed giving reflection peaks corresponding to successive roundtrip facet reflections. The roundtrip gain is then found by finding the ratio of the inverse Fourier transform of two such successive peaks. This method can include a correction due to the resolution bandwidth of the optical detector, however there are fluctuations on both sides of the wavelength range which depend on the window function used. Recently, the Fourier Series Expansion method was proposed to measure the gain spectrum from the ASE spectrum [8]. The FSE method also allows for an instrument response function if the instrument response can be measured, however there are no fluctuations at the side of the wavelength range as we expand over all the longitudinal modes of the laser. The round-trip gain (b) is determined by using a FSE of each longitudinal mode of the laser diode ASE spectrum. From the round-trip gain, the net modal gain \( g_{\text{net}} \) can be easily determined if both the facet reflectivity and the cavity length of the laser are known. Using the round-trip gain the linewidth enhancement factor (\( \alpha \)) can be calculated. A comparison of \( \alpha \) by using the H-P, FT and FSE methods are made for both InGaAsP and InGaAlAs laser diode material systems emitting near 1.3 \( \mu \)m.

Calculating the Linewidth Enhancement Factor

In order to calculate the linewidth enhancement factor we first need to calculate the round trip gain \( (b) \) of a Fabry-Perot laser which can be calculated from the measured ASE spectrum (Fig. 4.1) by a number of different methods, of which the most common and simplest to use is the H-P method where the round trip gain \( (b) \) is defined as

\[
b = \frac{1}{2L} \ln \left( \frac{r^{1/2} - 1}{r^{1/2} + 1} \right)
\]  

(4.7)

where \( L \) is the cavity length of the laser diode and \( r \) is the depth of modulation of the F-P resonances from
where \( P \) is the peak output power and \( V \) is the valley output power and the subscript \( i \) denotes the \( i \)th F-P resonance. As the round trip gain is defined as a quotient of both \( P \) and \( V \) the coupling efficiency is not important as long as the modes are clearly visible in this below threshold regime. Using this method will underestimate the gain if the resolution bandwidth of the instrument used to record the ASE is poor.

\[
r_i = \frac{P_i + P_{i+1}}{2V_i}
\]

(4.8)

Figure 4.1: Measured ASE spectrum of the InGaAlAs semiconductor laser operating at 1.3\( \mu \)m at an optical spectrum analyser bandwidth resolution of 0.1 nm.
Using the Fourier Transform method to calculate the round trip gain is more accurate as a system response function can be included so any bandwidth of the instrument will yield an accurate result. However, there will be fluctuations at the edges of the gain spectrum due to the window function used in calculating the Fourier Transform. This method is described below.

The ASE spectrum of a Fabry-Pérot (FP) semiconductor laser diode can be described from [9] as

\[ I(\beta) = \frac{(1-R)^2}{R} \frac{b}{1+b^2-2b \cos(4\pi\beta n L)} \]  \hspace{1cm} (4.9)

where \( R \) is the facet reflectivity, \( L \) is the laser cavity length, \( \beta \) is the wavenumber \( \beta = 2\pi/\lambda \), \( n \) is the refractive index and \( b \) is the round trip gain. The cosine factor can be expressed as an infinite series of exponential functions i.e.

\[ I(\beta) = \frac{(1-R)^2}{R} \frac{b}{1+b^2} \sum_{m=-\infty}^{\infty} b_m \exp(i4\pi mL\beta m) \] \hspace{1cm} (4.10)

The net mode gain is related to the round trip gain through
\[ b(\beta) = \exp[g(\beta)L]R \]  
(4.11)

where both the net mode gain \( g(\beta) \) and the round trip gain \( b(\beta) \) are wavelength dependent. The Fourier Transform (FT) of (4.10) is

\[
I(z) = \frac{1}{\pi} \int_{-\infty}^{\infty} I(\beta) \exp(-i2\pi\beta z) d\beta
\]  
(4.12)

This FT spectrum will consist of a series of peaks symmetrical to \( z = 0 \). Taking the two peaks centred at \( z = 0 \) and \( z = 2nL \) we obtain the round trip gain from

\[
b(\beta) = \frac{\int_{-nL}^{nL} I(z)dz}{\int_{-nL}^{nL} \tilde{I}(z)dz}
\]  
(4.13)

Because the measured ASE spectrum is wavelength-range limited, which is like multiplying the ASE spectrum by a rectangular window the \( b \) values will be affected. To decrease this effect the entire ASE spectrum is multiplied by the Hanning window function before the FT is preformed which gives the modified ASE nearly zero values at the sides of the window as described in [10]. Here a response function is included as in [10] due to the finite bandwidth of the optical spectrum analyser used. In practice the measured ASE spectrum is a convolution of an intrinsic ASE spectrum \( I(\lambda) \) with the response function \( f(\lambda' - \lambda) \) of the OSA where

\[
I'(\lambda') = \int_{-\infty}^{\infty} I(\lambda) f(\lambda' - \lambda) d\lambda
\]  
(4.14)

By expressing \( \lambda' - \lambda \) as \( \delta \lambda \), transforming to the wavenumber domain an using the similarity and convolution theory of FT theory [10] we can express (4.14) as

\[
\tilde{I}'(z) = \int_{-\infty}^{\infty} I(\beta) \exp(-i2\pi\beta z) F(z, \beta') d\beta
\]  
(4.15)

Where

\[
F(z, \beta') \approx \int_{-\infty}^{\infty} f(\delta \lambda) \exp(i2\pi\beta'^2 \delta \lambda) d\delta \lambda
\]  
(4.16)
Because the response function is only nonzero in a very narrow region around $\delta \lambda = 0$, we can approximate $\beta' \beta = \beta^2$ and $\beta^2 \approx \beta'^2$ therefore the FT of the intrinsic ASE spectrum can be calculated from

$$\bar{I}(z) = \frac{\bar{I}'(z)}{F(z, \beta')}$$

(4.17)

Therefore we can define the round trip gain ($b$) as

$$b(\beta) = \left| \frac{\int_{-nL}^{nL} \frac{\bar{I}'(z)}{F(z, \beta')} dz}{\int_{-nL}^{nL} F(z, \beta) dz} \right|$$

(4.18)

where the integrals are over the first and second peaks in the Fourier transformed spectra. This method will not underestimate the gain due to the correction factor. In practice the response function of the OSA is found by measuring the spectrum of an external cavity laser (ECL) at the wavelength of interest. The linewidth of the ECL is about 100 kHz which can be ignored in comparison with the OSA resolution bandwidth. The measured spectral responses of the OSA are shown in figure 4.3 while the calculated FT round trip gain not including the OSA response function is shown in figure 4.4.

Figure 4.3. Response function of ECL measured with the resolution of the OSA to be $\Delta \lambda = 0.06, 0.1, 0.2$ nm.
The Fourier Series Expansion method can also be used to calculate the round trip gain and again an instrument response can be included to yield an accurate result. The FSE method is more accurate at the edges of the ASE spectrum than the Fourier transform method as no window function is used and the expansion is over each longitudinal mode of the ASE. The ASE spectra of a semiconductor Fabry-Pérot (F-P) laser can be described as

\[ I(\beta) = I_s(\beta) \frac{(1 - R)[1 + b(\beta)]}{1 + b^2(\beta) - 2b(\beta)\cos[\phi(\beta)]} \]  \hspace{1cm} (4.19)

where \( \beta = 2\pi/\lambda \) is the wavenumber, \( I_s(\beta) \) is the single pass ASE, \( R \) is the reflectivity and \( b(\beta) \) is the round trip gain which is defined as

\[ b(\beta) = \exp[g(\beta)L]R \]  \hspace{1cm} (4.20)

where \( g(\beta) \) is the net mode gain, \( L \) is the cavity length and the phase \( \phi(\beta) \) is defined as

\[ \phi(\beta) = 2L\beta n(\beta) \]  \hspace{1cm} (4.21)
where \( n(\beta) \) is the effective index. If we consider just one longitudinal mode around \( \beta_0 \) (which is the mode peak wavenumber) as shown schematically in figure 4.5 below, the phase \( \phi(\beta) \) can be approximated as

\[
\phi(\beta) \approx \phi(\beta_0) + 2L(\beta - \beta_0)n_g(\beta_0)
\]  

(4.22)

where \( n_g(\beta_0) \) is the group refractive index and is wavelength dependent.

We can periodically extend the longitudinal mode and calculate the Fourier series coefficients as

\[
\tilde{I}_m = \frac{1}{2\pi} \int_{-\pi}^{\pi} I(\phi)\exp(-im\phi) d\phi
\]  

(4.23)

Taking the wavenumber as the argument (4.23) can be written as

\[
\tilde{I}_m = \frac{1}{\Delta\beta} \int_{\beta-\pi}^{\beta+\pi} I(\beta)\exp\left[-i\frac{2m\pi}{\Delta\beta}(\beta - \beta_0)\right] d\beta
\]  

(4.24)

The round trip gain is found by finding the ratio of successive Fourier coefficients.

\[
b(\beta_0) = \frac{\tilde{I}_{m+1}}{\tilde{I}_m}
\]  

(4.25)

where \( m \) is the \( m^{th} \) Fourier coefficient number and \( \tilde{I}_m \) and \( \tilde{I}_{m+1} \) are two successive Fourier coefficients from the expansion of (4.24). \( I_0 \) would be the zeroth-order
coefficient which is equal to the average intensity used by Cassidy [11]. $\beta_0$ is the wavenumber corresponding to the peak of each individual mode and $\Delta \beta$ is the wavenumber interval over the longitudinal mode. However, the round trip gain calculated by this method is still dependent on the OSA bandwidth resolution. We can again introduce an OSA instrument response function similarly to that for the FT method so that this dependence is removed. Therefore (4.25) becomes

$$b(\beta_0) = C_m \frac{I_{m+1}}{I_m}$$

(4.26)

where $C_m$ is an OSA instrument response function.

![Figure 4.6: The Round trip gain calculated using the Fourier transform method, the Fourier series expansion method with and without the OSA response function and the Hakki-Paoli method at 0.2 nm OSA resolution bandwidth.](image)

All three methods underestimate the gain at resolutions down to $\sim 0.1$ nm. The FSE method with the OSA response function included is also shown in figure 4.6 which shows a larger gain which is nearer its true value. With the response function an error of 2% in gain is observed over the OSA resolution bandwidth of 0.06 to 0.2, while
without it an error of ~ 7% over the same the same resolution bandwidth is observed as reported in [10]

Using any of these methods if the mirror reflectivities are known the net mode gain can be calculated from the round trip gain as:

\[ g = \frac{1}{L} \ln(b(\beta)) - \frac{1}{2 \cdot L} \ln R \]  

(4.27)

Here R is the product of the mirror reflectivities. As the net mode gain is calculated from the round trip gain it includes an instrument response correction in both the FT and FSE methods.

![Net Modal Gain calculated using the Fourier Series Expansion method with the OSA response function included.](image)

Figure. 4.7: The Net Modal Gain calculated using the Fourier Series Expansion method with the OSA response function included.

Here two different methods to calculate the linewidth enhancement factor one for the H-P and the FSE methods and another for the FT method as a comparison are described. For the H-P and FSE methods in order to determine the linewidth enhancement factor \( \alpha \), we first need to measure the ASE of the F-P laser under increasing injection currents up to the threshold current, see figure 4.8. However, the mode spacing must be larger than the induced mode shift due to the increase in carrier density (N) or else there will be an uncertainty when calculating the average
wavelength shift. We then determine the round-trip gain of the F-P laser by the H-P or FSE methods at a range of injection currents up to threshold. \( \alpha \) can be defined as the ratio of the change of the refractive index \( n \) with carrier density \( N \) to the change in the natural log of the round-trip gain \( (\ln b) \) with carrier density \( N \) and is expressed as:

\[
\alpha = -\frac{4\pi}{\lambda} \frac{dn/dN}{d(\ln b)/dN}
\]  

(4.28)

The change in mode refractive index \( dn \) can be determined from the wavelength shift \( d\lambda \) of the Fabry-Perot mode with the change in injection current below threshold according to the relation:

\[
dn = (\lambda/2L\Delta\lambda)d\lambda
\]  

(4.29)

where \( \Delta\lambda \) is the Fabry-Perot mode spacing, \( \lambda \) is the nominal wavelength (1310 nm), and \( d\lambda \) is the wavelength shift when the current is varied by \( dl \). Combining equations (4.28) and (4.29):
\[ \alpha = \frac{2\pi}{L\Delta\lambda} \frac{d\lambda}{d(\ln b)} \]  

(4.30)

The variation of the group effective index \( (n_g) \) with wavelength can also be calculated from (4.29) as

\[ n_g = n - \frac{\lambda}{d\lambda} \frac{dn}{d\lambda} \]  

(4.31)

where the group effective index is the group index due to the different layers in the laser. The group index is dependent on the group velocity (or signal velocity) of the light wave whereas the refractive index is dependent on the phase velocity of the light wave. A step size of 0.5 mA was chosen so that the entire wavelength shift as the injection current is increased is less than the mode spacing of the laser. Figure 4.9 shows \( \alpha \) calculated by the FSE method and the H-P method at 0.1 and 0.5 nm OSA bandwidth resolutions for an InGaAlAs laser diode operating at 1310 nm. It is not necessary to include the instrument response function in the round-trip gain calculation in the FSE method as \( \alpha \) depends only on the change in the round-trip gain with current. It can be clearly seen that the instrument bandwidth resolution has a large effect on \( \alpha \) with the H-P method while the FSE method is independent of the instrument bandwidth resolution.
Figure 4.9: Linewidth Enhancement Factor calculated by the FSE method and the H-P method at 0.1 and 0.5 nm OSA bandwidth resolutions with the continuous lines representing a second order polynomial fit.

Fig 4.10 shows the variation of the linewidth enhancement factor for both the InGaAlAs and InGaAsP laser diodes with wavelength. From Figure 4.10, we see that \( \alpha \) increases as the wavelength increases due to the fact that the density of states at the long wavelength (lower energy) end is mostly filled compared to the short wavelength (higher energy) end. Therefore the change of gain with carrier density change at the long wavelength end will be smaller than the change of gain at the short wavelength end.
The linewidth enhancement factor can also be calculated by another method which is a slight change to the method described in [2] and which is used to demonstrate the FT method. To use this method we first calculate the phase across the wavelength range of interest ($\phi$) (here 1295 nm to 1325 nm), by using (4.32).

$$\phi = 4 \cdot \pi \cdot \beta \cdot n \cdot L - \phi_0$$  \hspace{1cm} (4.32)

where $\beta$ is the wavenumber, $n$ is the effective refractive index and $L$ is the cavity length. We also have a random phase factor ($\phi_0$), however as we need only the change in the phase with injection current from (4.33) this unknown random phase factor will cancel.

$$\frac{dn'}{dl} = \frac{1}{4 \cdot \pi \cdot \beta \cdot L} \cdot \frac{d\phi}{dl}$$  \hspace{1cm} (4.33)

where $dn/dl$ is the change in effective refractive index with injection current which is directly proportional to $dn/dN$. Also the change in gain with injection current is defined as
\[ \frac{dg}{dI} = \frac{1}{L} \cdot \frac{d \ln(b)}{dI} \]  

(4.34)

From (4.6) the linewidth enhancement factor can then be calculated as

\[ \alpha = -\frac{4 \pi}{\lambda} \frac{\delta n}{\delta N} \]  

(4.35)

which when combined with (4.33) and (4.34) gives

\[ \alpha = -\frac{\frac{d \phi}{dI}}{\frac{d \ln(b)}{dI}} \]  

(4.36)

However due to an unknown factor \( \varphi_0 \) in (4.33) we cannot use the exponential form of \( \varphi_0 \) in equation (4.36) and must break it down to its sine and cosine terms as in (4.37).

Finally to calculate the linewidth enhancement factor we use equation (4.38).

\[ \frac{d \phi}{dI} = \frac{d \phi}{d \cos(\phi)} \cdot \frac{d \cos(\phi)}{dI} = \frac{1}{d \cos(\phi)} \cdot \frac{d \cos(\phi)}{dI} = -\sin(\phi) \cdot \frac{d \cos(\phi)}{dI} \]  

(4.37)

\[ \alpha = -\sin(\phi) \cdot \frac{d \ln(b)}{dI} = \frac{d \cos(\phi)}{\sin(\phi) \cdot d \ln(b)} \]  

(4.38)

Figure 4.11 shows the linewidth enhancement factor calculated by this method.
Figure. 4.11: Linewidth Enhancement Factor calculated by the FT method with the continuous lines representing a second order polynomial fit.

The Fourier transform method is computationally easier as for each point in the FSE and H-P methods the gain round trip gain must be also determined from the ASE. The linewidth enhancement factor calculated by three different methods for another laser diode based in InGaAlAs is shown in figure 4.12 below, the HP and FT methods show similar alpha values even though the FT method does make use of the OSA deconvolution as described above, therefore as it is known that the FSE method is more accurate than the HP method then the FT method is also less accurate than the FSE method.
Figure 4.12: Linewidth enhancement factor by the Hakki-Paoli, Fourier transform and Fourier series expansion methods.
Waveguide Loss

Introduction to waveguide loss

Optical waveguides are an important part of optical communication systems as light propagates between different optical components such as lasers, modulators, detectors etc. Characterising these waveguides is therefore of high importance. The performance of waveguides depends on many parameters including dispersion, transmission bandwidth and the optical propagation loss. The optical loss can be measured by numerous methods such as Hakki-Paoli (H-P) [12, 13], waveguide direct cut-back [14], prism coupling [15] and scattered light collection methods [16, 17]. However, most of these methods have limitations such as in the waveguide direct cut-back method, the coupling and the cleaved facet must be exactly the same before and after cutting which is very problematic, the prism coupling technique can only be applied to buried strip waveguides and not to ridge waveguides. The H-P method works well for low-loss waveguides however it is applied to the transmission spectrum and as such access to both facets is required. Here two methods to determine the optical loss of a laser diode from the reflection spectrum are described and the waveguide loss of two different Fabry-Perot (F-P) laser diodes determined. The first method that was used is based on the H-P method which has been combined with the transmission spectrum to measure the waveguide loss as well as the facet reflectivity [18, 19]. However, as pointed out in [20], these kinds of measurements become problematic if the reflection of the launching optical field deviates from the reflection of the waveguide mode at the waveguide facet, which unfortunately is the general case since the reflection of the launching mode depends sensitively on its mode profile and the incident angle. If assuming that the reflection of the launching mode at the facet is generally different from the reflection of the waveguide mode, the reflection spectrum would become difficult to use. Here, we measured the waveguide loss from just the reflection spectrum based on the Fourier series expansion method [3, 8].

Instead of using the ratio between the first harmonic and the dc term, we use the ratio between the second and the first harmonic terms. As is clear from the analysis below, the uncertainty caused by the direct reflection ($r_1$) of the launching
mode can then be bypassed. Shown below in figure 4.13 is a schematic of a lensed fibre coupled to a waveguide showing the amplitude reflections from the facets r and the initial reflected amplitude as the light is coupled from the lens fibre to the waveguide.

![Figure 4.13. Lens fibre coupled to a semiconductor laser waveguide](image)

The reflection spectrum measured will include two parts: one is the direct reflection of the launching mode from the waveguide facet, the other is the light coupled into the waveguide and reflected back through the FP cavity. Similarly to the calculations of the reflection and transmission as determined in chapter 3 by the scattering matrix method the total reflection amplitude ($\chi$) can be expressed as

$$\chi = r_1 + \Gamma t^2 \frac{b}{r} \exp(-j\phi) \sum_{p=0}^{\infty} (b \exp(-j\phi))^p$$

where $r_1$ is the direct reflection coefficient from the front facet, $\Gamma$ is the coupling coefficient of light into the waveguide, $t$ and $r$ are transmission and reflection coefficients of the facets as normally incident with the waveguide mode inside the waveguide, $b = \exp(-\alpha l) R$, $R = r^2$, is the round-trip loss, $\alpha$ is the waveguide loss, $l$ is the waveguide length, $\phi = 2\beta n_{eff} l$ is the round-trip phase shift, $\beta$ is the wavenumber in vacuum and $n_{eff}$ is the effective index of the waveguide. As $r$, $t$, $b$ and $\phi$ all dependent on wavelength, the total amplitude reflection is also wavelength dependent. The measured power reflection spectrum ($X = |\chi|^2$) would be

$$X = r_1^2 + \frac{\Gamma^2 t^4 b^2}{R(1-b^2)} (1 + 2 \sum_{p=1}^{\infty} b^p \cos(p\phi)) + 2\Gamma t^2 \frac{b}{r} \sum_{p=0}^{\infty} b^p \cos((p+1)\phi)$$
where in (4.40) the exponential functions are replaced by the cosine functions as the absolute value squared of (4.39) is taken. The round-trip loss \( b \) can be calculated from the transmission spectrum modulation depth directly. Again the power reflection spectrum is wavelength dependent. However, this process cannot be applied to the reflection spectrum because of the unknown direct reflection coefficient \( r_1 \) which is influenced very much by the launching optical field profile and the incident angle. It could be different from measurement to measurement.

This unknown direct reflection can be overcame using the FSE method to calculate the gain as described above, assuming that we have measured the reflection spectrum which covers at least one longitudinal mode interval as shown in figure 4.14, we calculate the following Fourier series coefficients [8]

\[
\tilde{X}_0 = r'^2 + \frac{\Gamma^2 t^4 b^2}{R(1 - b^2)} \tag{4.41}
\]

\[
\tilde{X}_1 = \frac{\Gamma^2 t^4 b^3}{R(1 - b^3)} + \Gamma r'^2 \frac{b}{r} \tag{4.42}
\]

\[
\tilde{X}_2 = \tilde{X}_1 b \tag{4.43}
\]

So we can obtain the round-trip loss from

\[
b = C_m \frac{\tilde{X}_2}{\tilde{X}_1} \tag{4.44}
\]
where $C_m$ is the response function as described above.

Once we get the round-trip gain $(b)$ we can calculate the loss from $\alpha = -\ln(b/R)/l$, which is the standard process of the FP technique. For cleaved facets of III-V waveguides $R$ is close to 0.3. If $R$ is uncertain in practice, two waveguides with different lengths and similar other parameters can be measured simultaneously and loss can be calculated from $\alpha = -\Delta(\ln(b))/\Delta l$. The coupling conditions will not influence the loss extraction which is the merit of the FP technique.

Here two different methods to determine the internal loss of a waveguide are described – External Cavity Tunable Laser method and Broadband method.

**External Cavity Tunable Laser method to measure waveguide loss**

The experimental set-up used for this measurement is described below with a schematic in figure 4.15.

![Figure 4.15. Schematic of waveguide loss experimental set-up. ECL: External Cavity tunable Laser source; PC: Polarization controller; ISO: Isolator; PD: Photodiode; LD: Laser diode.](image)

The waveguide measured here is basically an InGaAlAs multi-quantum well FP laser diode. The peak gain wavelength is around 1480 nm at the laser threshold current. A simple 50:50 2×2 beam splitter was used to launch light into the laser diode and also receive the reflection. All the fibre connectors have angled facets to avoid unfavourable reflections. An isolator was placed before the photodiode because the photodiode has a small reflection which can impact on the measurement. The polarization controller which consists of a polarizer followed by a quarter-wave plate
and a half wave plate was used to set the launch light as the TE mode incident onto the laser diode. This was realized by treating the laser diode as a photodiode and maximizing the photocurrent by adjusting the wave plates in the polarization controller while launching 1510 nm light into it. A polarization maintaining antireflection coated lensed fibre with a spot size ~7 μm was used to couple to the laser diode. High coupling was obtained easily as the laser diode was forward biased and emission coupled into the lensed fibre monitored. The external tunable laser was scanned with a step of 0.02 nm from 1560 to 1590 nm and a constant power of 1.5 mW. The photocurrent recorded by a Keithley pico-ammeter is shown in figure 4.16. By applying the scheme introduced above, the results obtained are shown in figure 4.17. As analyzed in [21], using the ratio of the second and first harmonic would be more sensitive to the influence of noise. However, by averaging the results from multiple longitudinal modes, the results can be improved quite a lot because the noise influence reduces as more sampling points used in the Fourier series expansion process. The averaging is possible because the loss is always a slowly varying function of wavelength. By averaging the round-trip loss in the wavelength range between 1580 and 1590 nm, the value obtained finally is 0.173±0.009. With a facet reflection R = 0.3, the inner loss of the laser diode with a length around 350 μm would be 15.8±1.5 cm⁻¹. Typical values for waveguide loss are from 10 – 20 cm⁻¹ for InGaAlAs with variations over this range even for lasers grown on the same wafer. To confirm the result we also measured the amplified spontaneous emission in the long wavelength end of the ASE spectrum [22]. The current injected into the laser was 12 mA which is already close to the threshold current. The OSA resolution bandwidth was set at 0.1 nm. The Fourier expansion method was used to calculate the round trip gain [8]. The round trip gain and the round trip loss are shown together in figure 4.18 below. As seen from it, the round-trip loss estimated from the ASE spectrum measurement agrees well with those derived from the reflection spectrum.
Figure 4.16. Reflection spectrum as measured with pico-ammeter.

Figure 4.17. Round trip gain measured from the reflection spectrum.
A paper describing this method to determine waveguide loss was published recently in [23].

**Broadband Method to measure waveguide loss**

Another way to measure the reflection spectrum is to use a broadband amplified spontaneous emission (ASE) source and use an optical spectrum analyser (OSA) to resolve the cavity spectrum. By doing so, unfavourable reflections from optical connectors do not disturb the measurement and reflection spectra with high signal-to-noise ratio can be very easily measured as seen from the following experiment. However, as we are using the OSA to resolve the cavity spectrum, the influence from the limited resolution bandwidth of the OSA must be taken into account. As shown in [3, 23], even when using a narrow linewidth single mode source to measure the transmission spectrum of a very low loss and very long GaAs waveguide, there could be resolution problems as well. In the above section and [3, 8] we have shown that a deconvolution process can be used to reduce the influence from the limited OSA resolution in the gain measurement through the ASE spectrum of the laser diode. Here this process is adapted for loss measurements from the reflection spectrum measured.
by an OSA and a broadband source and demonstrated that this is a simple and robust method to determine waveguide loss.

As in the ECL method to determine the waveguide loss described above, a Fourier series expansion is performed on each longitudinal mode in the reflection spectrum and (4.44) is used to determine the round trip gain. The Fourier coefficients relate to fundamental reflection from the front facet and the harmonics from each round-trip inside the waveguide. Again to avoid the influence from the direct reflection from the facet we use the first and second harmonic of each mode, which corresponds to one and two round-trips in the cavity, in the loss calculation:

\[ b(\beta_0) = \frac{\tilde{I}_2}{\tilde{I}_1} \]  

(4.45)

where \( \tilde{I}_m \) is the \( m^{th} \)-order Fourier Coefficient, \( b \) is the round-trip loss as described above from

\[ \tilde{I}_m = \frac{1}{\Delta \beta} \int_{\beta_{\Delta \beta}}^{\beta_{x \Delta \beta}} I(\beta) \exp \left[ -i \frac{2m\pi}{\Delta \beta} (\beta - \beta_0) \right] d\beta \]  

(4.46)

Again to overcome the intrinsic OSA resolution bandwidth limitation we include the deconvolution process as in the linewidth enhancement factor section and in [10, 24] by measuring the linewidth of a narrow linewidth laser (linewidth \( \sim 150 \) kHz) at specific OSA resolution bandwidths and use this to generate an OSA correction as

\[ b_{\text{new}}(\beta_0) = C_{\text{OSA}} \frac{\tilde{I}_2}{\tilde{I}_1} \]  

(4.47)

where

\[ C_{\text{OSA}} = \frac{\int_{-\infty}^{\infty} f(x) \exp(i2\pi x / \Delta \lambda) dx}{\int_{-\infty}^{\infty} f(x) \exp(i4\pi x / \Delta \lambda) dx} \]  

(4.48)

where \( \Delta \lambda \) is the longitudinal mode spacing and \( f(x) \) is the response function of the OSA at a certain resolution bandwidth. From the round-trip loss the internal optical
loss of the waveguide can easily be determined provided the facet reflectivity and cavity length are known from (4.27).

The experimental set-up used for this measurement is shown in figure 4.19. As the laser waveguide is polarization sensitive it is important to ensure just light polarized in the transverse-electric mode is excited in the cavity. As in the previous section, a polarization controller consisting of a polarizer followed by a quarter-wave plate and a half-wave plate, is inserted between the output of the broadband source (Erbium-doped-fibre-amplifier (EDFA)) and the laser waveguide under inspection. To do this the laser is used as a photodiode and the voltage across the laser is maximized by altering the quarter-wave plate and half-wave plate in the polarization controller as in [23].

A 2X2 optical splitter is inserted between the polarization controller and the laser waveguide to couple the reflection spectrum to the OSA. The reflected light from the laser waveguide is sent through an isolator just before the OSA to minimize any reflections from it. All coupling is through (anti-reflection) AR coated lens ended single mode fibre with angled connectors. The laser diode under inspection is an InGaAlAs multiple quantum well (MQW) laser with a cavity length of 350 \( \mu \text{m} \) and cleaved facets. At threshold the peak gain output is at 1485 nm. The longer wavelength side of the output from the EDFA (1551-1561) used for this measurement is below the bandgap of the laser. The measured reflection spectrum is averaged 100 times to reduce any influence of noise on the measurement.

![Diagram of broadband waveguide loss experimental set-up](image)

**Figure 4.19.** Schematic of broadband waveguide loss experimental set-up. EDFA: Erbium-doped-fibre-amplifier; PC: Polarization controller; ISO: Isolator; OSA: Optical Spectrum Analyser; LD: Laser diode.
The reflection spectrum recorded on the OSA using a 0.1 nm bandwidth resolution and averaged 100 times over a wavelength range of 10 nm from 1551nm to 1561 nm is shown in figure 4.20 below. The wavelength range from 1552 to 1562 is used as it is at the lower energy end of the spectrum and where the EDFA used has a large and relatively flat output power. This measurement could be extended to longer wavelengths if the EDFA used had a larger output power at these wavelengths.

This measured reflection spectrum is a convolution of the intrinsic reflection spectrum of the diode under test and the response of the OSA. The limit of the minimum resolution bandwidth of the OSA is overcome by using the deconvolution process described above. Figure 4.21 shows the round-trip loss versus the wavelength as calculated for the FSE both with and without the deconvolution process for 0.1 nm and 0.5 nm OSA bandwidth resolutions.
Figure 4.21. Round-trip loss against wavelength for 0.1 and 0.5 nm OSA bandwidth resolutions with and without deconvolution process.

From figure 4.21 we can clearly see the large influence that the deconvolution has for the 0.5 nm and a smaller influence for the 0.1 nm OSA bandwidth resolution scan. Without the deconvolution the round-trip loss is underestimated by ~ 0.01 and ~ 0.24 at OSA bandwidth resolutions for 0.1 nm and 0.5 nm respectively. With the deconvolution the round-trip loss is similar when the OSA resolution is 0.1 and 0.5 nm. Far from the bandgap in the wavelength range of 1551 to 1561 nm, the round trip gain calculated at 0.1 nm and 0.5 nm resolution bandwidth with the deconvolution process is $0.201 \pm 0.02$ and $0.203 \pm 0.02$ respectively which with a cavity length of 350 $\mu$m and facet reflection of 0.3 gives an internal optical loss of $11.40 \pm 0.96$ cm$^{-1}$ and $11.18 \pm 1.1$ cm$^{-1}$ respectively. The large difference between this and the previously measured waveguide loss of 15.8 cm$^{-1}$ is a result of measuring different waveguides.

A paper describing this method to determine waveguide loss was published recently [25].

The broadband method is easier and quicker to implement and is determined by the speed of the OSA wavelength scan while the ECL method is determined by the speed of the ECL tuning speed. This is an important factor as the reflection spectrum is quite weak even at high injection powers so if the modes are not clearly visible any
decrease in coupling will reduce the signal to noise. The maximum coupled output power from the EDFA through the splitter and polarization controller was <32 μW which is too low to observe the Fabry-Pérot modes far away from the operating wavelength which reduces the extent of this method.
Spontaneous Emission Factor and Internal Quantum Efficiency

**Spontaneous Emission and Quasi-Fermi Level**

Spontaneous emission is an important process in semiconductor lasers in that it influences laser linewidth, as well as the modulated response of a laser [26]. Spontaneous emission occurs when an excited electron decays to a lower energy state emitting a photon which is shown schematically in figure 4.22 below.

![Spontaneous emission schematic](image-url)

Figure 4.22. Spontaneous emission schematic

If there are a number (N) of electrons in an excited state then the rate which N decays is given by

$$\frac{dN}{dt} = -A_{21}N$$  \hspace{1cm} (4.49)

where $A_{21}$ is the rated of spontaneous emission and is termed Einstein A coefficient and has units of s$^{-1}$. Therefore as the number of carriers injected into a higher energy state is increased with increasing injection current, an increase in spontaneous emission is also observed with increasing injection current which is termed amplified spontaneous emission (ASE). For each spontaneous photon emitted another carrier must be injected into the active region of the laser diode and so spontaneous emission results in a decreased optical power output with injection current. From [5] the band diagram of a semiconductor laser can be shown as
where $R_{12}$ and $R_{21}$ are the rate per unit volume of transitions from the valence band to conduction band (absorption) and from the conduction band to the valence band (emission) respectively. These rates are dependent on the Fermi factors ($f_1$ and $f_2$) which describe the filled initial states and empty final states of a band. The three possible radiative transitions are the stimulated absorption $R_{12}$, stimulated emission $R_{21}$ and spontaneous emission $R_{\text{sp}}$ and these are dependent on the Fermi factors to the following extent

$$R_{12} = R_r f_1 (1 - f_2)$$

(4.50)

$$R_{21} = R_r f_2 (1 - f_1)$$

(4.51)

$$R_{\text{sp}} = R_r^{\text{vac}} f_1 (1 - f_2)$$

(4.52)

where $R_r$ is the radiative transition rate that would happen if all states in the conduction band were empty. $R_r^{\text{vac}}$ is dependent on the vacuum field strength $|e^{\text{vac}}|$. The vacuum field strength is a quantum mechanical description that describes the probability of adding a photon to a mode as being proportional to the amount of photons in that mode plus one. This imaginary photon field strength is what induces spontaneous emission of a photon. Here $f_1$ and $f_2$ are found from the quasi-Fermi levels $E_{FV}$ and $E_{FC}$ of the valence and conduction bands respectively from

$$f_i = \frac{1}{\exp\left(\frac{E_i - E_{FV}}{kT}\right) - 1}$$

(4.53)
and

\[ f_2 = \frac{1}{\exp\left(\frac{E_2 - E_{FC}}{kT}\right) - 1} \]  \hspace{1cm} (4.54)

and \( E_1 \) and \( E_2 \) are the energy levels of the valence and conduction bands respectively. From [27-29] the relationship between the material gain and the spontaneous emission can be defined as

\[ g_m(\omega) = \left[ 1 - \exp\left(\frac{\hbar \omega - \Delta F}{kT}\right) \right] g_{sp}(\omega) \]  \hspace{1cm} (4.55)

where \( \hbar \omega \) is the energy of a photon with angular frequency \( \omega \), absolute temperature \( T \), \( k \) is Boltzmann’s constant, \( \Delta F \) is the quasi-Fermi level separation and

\[ g_{sp}(\omega) = \frac{\pi^2 c^2}{n^2 \omega^2} r_{spon}(\omega) \]  \hspace{1cm} (4.56)

where \( n \) is the refractive index of the waveguide mode, \( c \) is the speed of light in vacuum and \( r_{spon}(\omega) \) is the frequency dependent spontaneous emission rate. Transferring into the wavelength regime we find that

\[ g_m(\lambda) = \frac{\lambda^4}{8\pi n^2} \left[ 1 - \exp\left(\frac{\hbar c}{\lambda} - \frac{\Delta F}{kT}\right) \right] r_{spon}(\lambda) \]  \hspace{1cm} (4.57)

as

\[ g_{sp}(\omega) = \frac{\pi^2 c^2 \lambda^2}{n^2 4\pi^2 c} \cdot \frac{\lambda^2}{2\pi c} r_{spon}(\lambda) \]  \hspace{1cm} (4.58)

which is found by setting the integrals

\[ \int r_{spon}(\omega) d\omega = \int r_{spon}(\lambda) d\lambda \]  \hspace{1cm} (4.59)
From [21-28] the ASE spectrum of a Fabry-Pérot semiconductor laser can be approximated by the following formula

\[ I = \frac{I_{sp}(1 - R)(1 + b)}{1 + b^2 - 2b \cos(2n_{eff} kL)} \]  (4.60)

where \( R \) is the facet power reflectivity, \( n_{eff} \) is the effective refractive index of the laser structure, \( L \) is the cavity length, \( k \) is the wavenumber in vacuum = \( 2\pi/\lambda \) where \( \lambda \) is the wavelength and \( b \) is the round trip gain

\[ b = \exp(gL)R \]  (4.61)

where \( g \) is the net mode gain, \( I_{sp} \) in (4.60) is the single pass ASE and is defined as

\[ I_{sp} = \frac{S[\exp(gL) - 1]}{g} \]  (4.62)

where \( S \) (which is related to the spontaneous emission per unit length) is related to the spontaneous emission rate \( r_{sp}(\lambda) \) by

\[ S = \frac{A\beta_{sp}r_{sp}hc}{\lambda} \]  (4.63)

where \( A \) is the quantum well cross section, \( hc \) is the energy of the light, and \( \beta_{sp} \) is the ratio of the spontaneous emission that is coupled into the waveguide mode of interest, and is also the inverse of the number of modes that lase. The spontaneous emission factor has been calculated using classical electromagnetic theory by [30] for index-guided structures and by [31] for gain and index-guided lasers and later expanded by [26]. The Fourier Transform (FT) of the ASE spectrum gives a series of peaks which correspond to harmonics of the optical round trip of the FP cavity. By inversely transforming the zeroth and first order peaks the following spectra can be determined

\[ I_0 = \left| \int_{-\infty}^{\infty} \tilde{I}(z) \exp(ikz)dz \right| = \frac{I_{sp}(1 - R)}{1 - b} \]  (4.64)

and
\[ I_1 = \left| \int_{n_o}^{n_f} \tilde{I}(z) \exp(ikz)dz \right| = bI_0 \] \hspace{1cm} (4.65)

where \( \tilde{I}(z) \) is the Fourier transformed ASE spectrum, therefore the round trip gain can be determined as

\[ b = \frac{I_1}{I_0} \] \hspace{1cm} (4.66)

therefore \( S \) the spontaneous emission coupled into the laser waveguide mode from (4.62), (4.63) and (4.64) is determined as

\[ S = \frac{I_0(1-b)g}{(1-R)[\exp(gL)-1]} \] \hspace{1cm} (4.67)

As the net mode gain is dependent on the material gain through

\[ g = \Gamma g_m - \alpha_i \] \hspace{1cm} (4.68)

where \( \alpha_i \) is the internal waveguide loss, substituting \( g_m \) from (4.57) into (4.68)

\[ g(\lambda) = C\lambda^5 S \left[ 1 - \exp \left( \frac{hc - \Delta F}{\lambda} \right) \right] - \alpha_i \] \hspace{1cm} (4.69)

where

\[ C = \frac{\Gamma}{8\pi^2 n^2 \hbar \beta_{sp} \xi} \] \hspace{1cm} (4.70)

where \( \xi \) is the coupling efficiency of the measured ASE spectrum (which from now on will be included in \( \beta_{sp} \) for simplicity) and \( r_{sp} \) from (4.57) becomes

\[ r_{sp} = \frac{S\lambda}{A\beta_{sp}hc} \] \hspace{1cm} (4.71)
with $\Gamma$ the confinement factor of the mode in the active region. Determining $C$ we can find the ratio of the spontaneous emission coupled to the waveguide mode.

**Quasi-Fermi Level Measurement**

The laser diode under inspection is an InGaAlAs multiple quantum well simple Fabry-Pérot laser diode with cleaved facets and a cavity length of 650 $\mu$m. The cleaved facets give a power reflectivity of 0.3. The device temperature is kept at a constant 40°C. The laser is biased just below threshold and the amplified spontaneous emission (ASE) spectrum is averaged 20 times and recorded on an optical spectrum analyser (OSA). The OSA resolution bandwidth is 0.1 nm. The finite resolution bandwidth of the OSA is overcome by using the same deconvolution process as defined above. An FT is performed on the recorded ASE spectrum which consists of a series of peaks corresponding to the harmonics of the cavity optical round trip and are shown in figure 4.24 below.

![ASE Spectrum](image)

Figure 4.24. Fourier transformed ASE spectrum with inset showing the recorded ASE spectrum.

Taking the ratio of the inverse Fourier transform of the fundamental and first harmonic gives the round trip gain as the fundamental peak is described as $I_0$ in (4.64) and the first harmonic peak as $I_1$ in (4.65) therefore the round trip gain is given by
The relationship between the round trip gain, the cavity length, the facet reflectivity and the net mode gain can be described by

\[ g = \frac{1}{L} \ln \left( \frac{b}{R} \right) \]  

(4.72)

The round trip gain and net mode gain calculated using the FT method with a similar deconvolution as that for the FSE method as described above in the section dealing with the linewidth enhancement factor are shown in figure 4.25.

Looking again at (4.69) the net modal gain \( g(\lambda) \) can be described as a linear function of \( q(\lambda, x) \) where \( x \) is the quasi-Fermi level separation \( \Delta F \) i.e.

\[ g(\lambda) = Cq(\lambda, \Delta F) - \alpha_i \]  

(4.74)

where \( C = \Gamma/8\pi e^2 n^2 h\beta A \) where \( A \) is the quantum well transverse area, and \( \beta \) is the spontaneous emission factor. Therefore \( \Delta F \) can be extracted using the following process. First \( \Delta F \) is estimated over a particular wavelength range, then the value of \( x \) is scanned and for each value of \( x \), a linear fit of \( q(\lambda, x)g(\lambda) \) is produced. From a value of \( x \) that gives a best linear fit the quasi-Fermi level separation can be deduced.

Figure 4.26 shows the norm of the residuals from the linear fit versus \( x \).
Figure 4.26 shows that the best linear fit occurs at a wavelength of 1523.8 nm. This corresponds to a quasi-Fermi level separation energy of ~ 0.814 eV (814meV) from

$$E = \frac{hc}{\lambda} = \frac{(3 \times 10^8)(4.1357 \times 10^{-15})}{1523.8 \times 10^{-9}}$$

(4.74)

with units given by

$$\frac{eV \cdot s \cdot m \cdot s^{-1}}{m} = eV$$

(4.75)

**Spontaneous emission factor**

The spontaneous emission factor ($\beta$) is a ratio of the spontaneous emission coupled into the waveguide mode and therefore it is a unit less number. The ASE spectrum given in (4.59) is in the wavenumber domain and can be easily transformed into the wavelength domain which is what is recorded as

$$I(\lambda) = \frac{I_{sp}(\lambda)(1-R)(1+b(\lambda))}{1 + b^2(\lambda) - 2b(\lambda) \cos \left( \frac{4\pi m_{eff} L}{\lambda} \right)}$$

(4.76)
where $I$ has the units of mW/nm as the optical power is recorded over some finite wavelength range. Therefore the single pass ASE (4.62) can be described as

$$ I_{sp}(\lambda) = \frac{S(\lambda)(\exp(g(\lambda)L)-1)}{g(\lambda)} \quad (4.77) $$

where $S$ is related to the spontaneous emission rate ($r_{sp}$) through (4.63). The spectrum measured by the OSA is a convolution process described by (4.14) i.e.

$$ I'(\lambda) = \int I(\lambda')f(\lambda - \lambda')d\lambda' \quad (4.78) $$

where $I'$ has units of mW and $f(\chi)$ is the response function of the OSA which is unit less. Therefore we need to include the wavelength over which the OSA records the optical power in (4.78) for the units of (4.76) and (4.78) to be consistent. To do this we need to find the power difference between the actual power inserted into the OSA and that recorded by the OSA. This is done by measuring the optical power on a power meter and determining the power drop when measured on the OSA. Then by recording a single mode narrow linewidth laser on the OSA the resolution bandwidth is determined as the single mode narrow signal is broadened by the OSA and the amount of broadening can be easily determined. This is the resolution over which the OSA records when set to a particular bandwidth resolution. The Fourier series expansion method with the deconvolution process to remove the finite bandwidth of the OSA is then used to determine the gain from this recorded power spectrum. Using this method the spontaneous emission factor can be determined. From $C$ in (4.73) and performing the above correction to the ASE the spontaneous emission factor is dimensionless and is determined as 0.015 and increased as shown in figure 4.27 as the injection current is increased below threshold. During the calculation of the spontaneous emission rate a value of 0.3 was used for the coupling efficiency which is estimated as shown in the next section. This value may be larger or smaller which will change the spontaneous emission rate greatly.
Figure 4.27. Spontaneous emission factor versus injection current.
Internal Quantum efficiency

As the internal loss can be easily and readily found using the method described above the internal quantum efficiency ($\eta_i$) of an above threshold laser can be determined by the following method. The $\eta_i$ is the probability that an injected carrier recombines radiatively in the active region thus contributing to the stimulated laser output. The $\eta_i$ will never be unity as some current will spread around the active region thus not entering the quantum well (QW) region $\eta_s$ (current spreading). Some of the current entering the active region will not enter the quantum well $\eta_{\text{inj}}$ (QW injection efficiency) and not all current entering the quantum well will radiatively recombine $\eta_r$ (radiative efficiency), however $\eta_r$ is very close to unity above threshold as the Fermi levels in the QW pin above threshold. In order to determine $\eta_i$, first the external differential quantum efficiency ($\eta_d$) has to be determined. The $\eta_d$ is an empirical calculation of the number of photons output from both sides per electron injected into the entire laser structure [5]. From [32] the $\eta_d$ of a semiconductor quantum well laser is determined from

$$n_d = \frac{2e}{h\nu} \frac{dP}{dl}$$  \hspace{1cm} (4.79)

where $e$ is the electronic charge, $h\nu$ is the photon energy of the laser light and $dP/dl$ is the slope of the output power as the injection is increased above threshold. The factor of 2 is due to $dP/dl$ being obtained from one facet while the total power differential is needed, this will be included in $dP/dl$ for convenience for the rest of this measurement. To obtain the power differential $dP/dl$, the laser power current curve is measured and a linear fit is performed above threshold. However, as the power output is depended on the coupling efficiency ($\Gamma_c$) and this parameter needs to be first determined. The coupling efficiency is dependent on the measurement system used and various set-ups will give a differing value of $\Gamma_c$. The exact value of $\Gamma_c$ is extremely difficult to determine however one method which gives a very good estimate is described below. While semiconductor lasers have asymmetric spot sizes related to the particular waveguide geometry, the output is approximately similar to a lensed fibre with a spot size of 2.5 $\mu$m given by manufactures used to collect the laser output light, therefore light emitted through such lens fibre acts somewhat similarly to
light emitted from a laser diode. In order to measure $I_c$, the output from a tunable external cavity laser (ECL) is sent down a lensed fibre with the output through the lensed end. This lensed fibre mimics the spot size of a laser diode and so the amount of light collected will be similar to that from a laser diode. The output from the lensed fibre is collected by an integrating sphere power meter as in figure 4.28 below. This is the total output from the lensed fibre and is used as a reference termed $P_{ref}$.

![Figure 4.28](image)

Figure 4.28. Set up 1 - Total power measurement, ECL – external cavity tunable laser

The coupled power from all the measurements described in this thesis is determined by placing a collecting lens after the lensed fibre and recording the maximum power detected by the integrating sphere power meter as the lengths between the lensed fibre, collecting lens and the integrating sphere power meter as described in figure 4.29 below are adjusted.

![Figure 4.29](image)

Figure 4.29. Set up 2 - Coupled power measurement.

This power ($P_c$) is

$$P_c = \Gamma_c P_{ref}$$

(4.80)

therefore the coupling efficiency can easily be determined and a value of $\sim 0.3 = 30\%$ is obtained for $\Gamma_c$. 

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The slope efficiency can now be accurately determined from the above threshold power current relationship, however we multiply this by 2 to determine the total power output versus injected current from both facets of the laser provided they both have the same reflectivity. Figure 4.30 shows three power current relationships. The PI curve is the measured output power from one mirror versus injected current for the laser diode. The coupling influenced curve is the measured PI curve with the influenced of the coupling removed i.e. the total output from the laser as would be if the laser output power was measured by the set-up shown in figure 4.28 above. The coupling and both facets depicts the total output power from the laser diode taking both facets into account this is just the coupling influenced X 2.

![Figure 4.30. Power-Current curves showing the measured power, the power with the coupling efficiency included and the total output power versus injection current.](image)

Therefore a value of $\eta_d$ can now be found using $\frac{dP_{tot}}{dl} = 0.21$ (mW/mA) using the blue curve in figure 4.30.

$$\eta_d = \frac{e}{h \nu} \frac{dP_{tot}}{dl}$$

(4.81)

where $e/\nu$ for light of 1550 nm is $\sim 1.25 \ V$, therefore $\eta_d = 0.2625$. As we can determine the internal loss easily and is estimated to be $\alpha_i = 23 \ \text{cm}^{-1}$ using the methods described above in the section on waveguide loss. This is a higher loss and
again is from a different device to those described in the previous sections. From [33] the internal quantum efficiency can be measured from

$$\eta_i = \eta_d \left( \frac{\alpha_m + \alpha_l}{\alpha_m} \right)$$  \hspace{1cm} (4.82)

where $\alpha_m$ is the mirror loss which is determined from the cavity length ($L$) and the facet reflectivity ($R$), as

$$\alpha_m = \left( \frac{1}{L} \right) \ln \left( \frac{1}{R} \right)$$  \hspace{1cm} (4.83)

The cavity length can be calculated from the mode spacing of the laser from the spectral output and for this particular Fabry-Pérot laser with cleaved facets the facet power reflectivity is generally given as $\sim 0.3$. Therefore the mirror loss is $\alpha_m = 18.5$ cm$^{-1}$ for a laser diode cavity length of 650 $\mu$m as calculated from the mode spacing of the longitudinal modes of the laser diode. Using these values the internal quantum efficiency can be calculated from

$$\eta_i = \frac{e}{h \nu} \frac{dP_{tot}}{dl} \left( \frac{\alpha_l + \left( \frac{1}{L} \ln \frac{1}{R} \right)}{\left( \frac{1}{L} \ln \frac{1}{R} \right)} \right) \approx 0.6 = 60\%$$  \hspace{1cm} (4.84)

Therefore the internal quantum efficiency of the Fabry-Pérot under inspection was calculated to be 60 %.

Conclusion
The linewidth enhancement factor value is an important value for a more detailed theoretical model of laser diodes based on the InGaAlAs material system. Also a larger linewidth enhancement factor may give increased tunability of the laser output wavelength. The loss of the waveguides presented here are important values also as the waveguide loss must be included into any model of laser structures. The internal quantum efficiency is also an important parameter in laser modelling, while the coupling efficiency is important for determining the total power output from a laser diode and not just that collected at the facet.
References


Chapter 5 - Single Slot Laser Diodes

Introduction to slotted lasers

The simplest type of semiconductor laser to describe is the Fabry-Pérot (FP) laser which was modelled using the scattering matrix method (SMM) in chapter 3. In this chapter, an introduction to the single slot laser as a means to control the mode selectivity of the Fabry-Pérot (FP) laser is given. These lasers are fabricated by etching slots into the waveguide of the FP laser diode as described in [1-7]. The slots act as reflection centres and produce a modulation of the reflection and transmission spectra dependent on the characteristics of the slot such as slot position, slot depth to which it is etched and slot width. Even though the slot is not etched into the active (waveguiding) regions it will still interact with the mode of the electric field (and magnetic field) as the mode profile is not fully confined to the active region and will expand into the surrounding cladding regions. Figure 5.1 shows the laser diode schematic with one slot etched into the ridge of the waveguide. The 1D first, second and third order modes modelled using the finite difference time domain (FDTD) technique for a 2.5 μm structure with active region depth of 1 μm, upper cladding region of 1 μm and lower cladding of 1 μm with active region refractive index of 3.55 and cladding region refractive index 3.41, are shown below in figure 5.2.

Figure. 5.1 Single slot laser showing the etched slot into the ridge of the waveguide – slot not to scale
Figure 5.2. Mode profile of first three modes and refractive index profile through the laser structure.
From the above graph the fundamental mode is seen to penetrate into the cladding region so any perturbation in this area will influence the mode profile of the laser diode.

Theoretical modelling of single slot lasers

Slot Depth

Using the scattering matrix method (SMM) as outlined in chapter 3, we define the slot by the strength of the slot reflection \((r)\) and slot transmission \((t)\) thereby any slot loss \((\alpha_s)\) is determined by the following relationship

\[
\alpha_s = 1 - |r|^2 - |t|^2 \approx 2(1 - |t|)
\]  

(5.1)

assuming \(r \ll 1\), where \(r\) is the amplitude reflection, \(t\) is the amplitude transmission and \(\alpha_s\) is the amplitude loss.

The scattering matrix method [8, 9] is used to determine the slot reflection and transmission as a function of the slot etched depth and is shown in figure 5.3 below. Two different slot depths are shown in figure 5.4, a deep and shallow etch. For the modelled results presented here values of reflection and transmission are used from table 5.1 from [9] and from figure 5.3 we take an amplitude reflection of 0.00147 and an amplitude transmission of 0.972.
Figure 5.3. Reflection and transmission versus slot depth.

Figure 5.4. Deep and shallow etched slot.

Shallow etch    1 µm    Deep etch

| Interface   | $|r|$   | $|s|$   | Power loss (dB) |
|-------------|--------|--------|-----------------|
| TMM SMM     | TMM SMM| TMM SMM|                 |
| WG to Slot  | 0.004  | 0.0143 | 0.99 0.972 0 0.247 |
| Slot to WG  | 0.004  | 0.00037| 0.99 0.972 0 0.247 |

WG represents waveguide in table.

Table 5.1 TMM and SMM values for slot parameters taken from [9].
Slot Width

The influence of the slot width on the reflection and transmission is described here. Assuming the power reflectivity of the slot is $R = r^2$, as the slot is etched only into the cladding region around the active region it interacts with a small portion of the mode where $\Gamma$ is the optical confinement factor of the cladding layer. Then the reflected power is $\Gamma R$ and after the reflected power couples back into the mode again, the power reflectivity for the whole mode becomes $\Gamma^2 R$ and the amplitude reflection becomes $\Gamma r$. The optical confinement ($\Gamma$) is calculated to be 0.036 and 0.00075 using the two dimensional scattering matrix method as shown in [9] for the waveguide to slot and slot to waveguide interfaces respectively. The differences in these values are evident from the following analysis. The waveguide before the slot interface has good optical confinement and this means that a large percentage of the mode will be influenced by the waveguide to slot interface. After this interface the material is air which has a very low mode confinement, therefore the mode does not regenerate before the slot to waveguide interface, this is described schematically below in figure 5.5

![Figure 5.5 Schematic of mode and slot overlap.](image)

This schematic shows why there is little reflection from the slot to waveguide interface as the mode is very weakly confined in this area and so does not "see" the interface. The power loss is determined from the mode mismatch across the slot interfaces and is the same for both interfaces. Using the SMM the reflection, transmission, phase and mirror loss can be determined for lasers employing multiple or single slots. This difference is shown in Figure 5.6 where the SMM and TMM are used to describe the variation of slot width on the amplitude reflection.
The large scale Fabry-Pérot (FP) resonances seen in the TMM model are not visible in the SMM model as the cavity formed by the slot is asymmetric with respect to the reflection from and transmission through its interfaces. This SMM result agrees with what is reported in [7].

**Single Slot Laser**

Here an analysis is done for single slot lasers using the SMM, using the above values for amplitude reflection ($r_3$) and amplitude transmission ($t_3$) of the waveguide to slot and amplitude reflection ($r_1$) and amplitude transmission ($t_1$) of the slot to waveguide of ($r_3 = 0.0143$, $r_1 = 0.00037$, $t_1 = 0.972$, $t_3 = 0.972$). First a simple FP laser is modelled as in chapter 3, with a cleaved facet with amplitude reflection ($r_2$) of 0.55 and amplitude transmission ($t_2$) of 0.835 and the other facet is taken to be the etched slot with waveguide to slot interface reflection and transmission. In this model the slot is placed 100 μm from the front and 300 μm from the back of the laser cavity. The slot width along the propagation direction is taken as 1 μm. As an analogy with the modelled FP laser in chapter 3, the reflection and transmission amplitudes of a single
slot laser can be found from an effective cavity model through the SMM as depicted in figure 5.7 and figure 5.8.

![Figure 5.7. Single slot schematic showing three sections representing front, slot and back sections – not to scale.](image)

![Figure 5.8. Schematic of back section showing the SMM parameters](image)

where $L$ is the section length, $n_3$ is the slot region effective refractive index, $n_2$ is the back section refractive index, $n_1$ is the refractive index of air and $a_1$, $a_2$, $b_1$, $b_2$, $a'_1$, $a'_2$, $b'_1$ and $b'_2$ are the field amplitudes at the interfaces shown in the figure in the direction of their respective arrows and $\exp(-\beta L)$ determines how the field changes along the section. Initially setting $a_2$ to zero we can determine the outputs as function of the inputs as:

$$b_1 = a_1 r_1 + a'_1$$  \hspace{1cm} (5.2)

$$b'_1 = a_1 t_1 - a'_1 r_1$$  \hspace{1cm} (5.3)

$$b'_2 = a'_2 r_2$$  \hspace{1cm} (5.4)
solving for the scattering matrix \( S_{b11} \) which is the reflection from the left side of the whole section we get:

\[
S_{b11} = r_1 \left( t_2 r_2 \frac{(-t_1) \exp(-2i\bar{\beta}L)}{1 - r_2 (-r_1) \exp(-2i\bar{\beta}L)} \right) \tag{5.8}
\]

and solving for the scattering matrix \( S_{b12} \) which is the transmission through the section from the left side we get:

\[
S_{b21} = \frac{t_2 t_2 \exp(-i\bar{\beta}L)}{1 - r_2 (-r_1) \exp(-2i\bar{\beta}L)} \tag{5.9}
\]

similarly with setting \( a_1 \) equal to zero we find the reflection from the right side and the transmission through the section from the right side as:

\[
S_{b22} = -r_2 \left( t_2 (-r_2)(-t_2) \frac{\exp(-2i\bar{\beta}L)}{1 - r_2 (-r_1) \exp(-2i\bar{\beta}L)} \right) \tag{5.10}
\]

\[
S_{b12} = S_{b21} \tag{5.11}
\]

where \( \bar{\beta} \) is the complex propagation constant consisting of both the real \((\beta_{re})\) and imaginary parts \((i\beta_i)\) of the propagation constant:

\[
\bar{\beta} = \beta_{re} + i\beta_i \tag{5.12}
\]

\[
\beta_{re} = \frac{2\pi \eta_3}{\lambda} \tag{5.13}
\]

where \( \lambda \) is the wavelength and
\[ i\beta_i = \frac{g}{2} \]  

(5.14)

where \( g \) is the net modal optical gain (or loss as \( g = -\alpha \)).

\( S_{b11}, S_{b22}, S_{b21} \) and \( S_{b12} \) are the amplitude reflection and amplitude transmission, of and through this section respectively. The optical gain has a factor of 2 as it relates to the power whereas the SMM quantities relate to the amplitude, the optical gain used for the modelled results obtained below was experimentally determined from a Fabry-Pérot laser diode and is displayed in figure 5.9 below.

![Net Mode Gain versus Wavelength](image)

**Figure 5.9.** Net mode gain versus wavelength used in these simulations

\( S_{b11}, S_{b12}, S_{b21} \) and \( S_{b22} \) are the required SMM parameters for the back section. Using the same technique we can build up scattering matrixes for a laser structure with any amount of slots by combining each section’s scattering matrix in the next section as shown below.

A laser with a F-P cavity and one slot at the left hand side would have effective scattering matrices of:

\[
S_{s11} = r_3 + \frac{t_3 S_{b11}(-t_3)\exp(-2i\beta_s L_s)}{1 - S_{b11}(-r_3)\exp(-2i\beta_s L_s)}
\]

(5.15)
\[ S_{S12} = \frac{t_3 S_{b12} \exp(-i\tilde{\beta}_s L_s)}{1 - S_{b11}(-r_3)\exp(-2i\tilde{\beta}_s L_s)} \]  
(5.16)

\[ S_{S22} = S_{b22} + \frac{S_{b12}(-r_3)(S_{b21})\exp(-2i\tilde{\beta}_s L_s)}{1 - S_{b11}(-r_3)\exp(-2i\tilde{\beta}_s L_s)} \]  
(5.17)

\[ S_{S12} = S_{S21} \]  
(5.18)

where \( L_s \) is the length of the slot region, shown schematically below.

---

Expanding to a cavity with two FP sections and a single slot inside is achieved by repeating the above procedure with \( S_{S11} \) instead of \( S_{b11} \) and using the F-P section gain as described for the first FP section above and section cavity length. This gives the full SMM for a single slot laser diode with facet reflectivities defined by \( r_1 \) and \( r_4 \).

The full SMM equations are

\[ S_{total11} = r_4 + \frac{t_4 S_{s11}(-t_4)\exp(-2i\tilde{\beta}L)}{1 - S_{s11}(-r_4)\exp(-2i\tilde{\beta}L)} \]  
(5.19)

\[ S_{total12} = \frac{t_4 S_{s12} \exp(-i\tilde{\beta}L)}{1 - S_{s11}(-r_4)\exp(-2i\tilde{\beta}L)} \]  
(5.20)
\[ S_{\text{total}22} = S_{S22} + \frac{S_{S12}(-r_4)(S_{S21}) \exp(-2i\beta L)}{1 - S_{S11}(-r_4)\exp(-2i\beta L)} \]  

(5.21)

\[ S_{\text{total}12} = S_{\text{total}21} \]  

(5.22)

Using these equations the reflection, transmission and output from this device can be modelled. The device effective SMM is shown schematically below.

![Effective SMM single slot schematic](image)

Figure 5.11. Effective SMM single slot schematic.

The power reflection and transmission can be found by taking the absolutes squares of \( S_{\text{total}11} \) and \( S_{\text{total}12} \) and are shown in figure 5.12 and 5.13 respectively below.

![Single slot power reflection versus wavelength](image)

Figure 5.12. Single slot power reflection versus wavelength
The power reflection and power transmission graphs, figures 5.12 and 5.13 clearly show a modulation of the reflection and transmission spectra compared to a FP laser diode due to the presence of the slot. The slot produces a periodic modulation with every third cavity mode enhanced from which the slot position can be roughly determined as $1/3^{rd}$ of the cavity length. In the next section a more accurate determination of the slot position is given using the Fourier transform method.

**Angled Slots**

The position of the slot inside the laser cavity can be easily controlled with high accuracy, however the facet cleaving is less accurate and so if the slot position is of high importance then the position of the cleave relative to the slot has to be determined and controlled accurately. By removing most of the reflections from one side of the slot by angling one slot interface we remove this dependence of the cleave from this angled side as we have seen that each waveguide to slot interface only reflects, while each slot to waveguide interface has very small reflections. This is depicted schematically in figure 5.14 below for backward and forward travelling waves.
Having both slots with straight interfaces (1) will provide the largest modulation of the output spectrum, although if the slot interface that is farthest from the output facet is angled (2) then very little change in modulation of the output compared to the straight slot interfaces is seen. Angling of the slot interface nearest to the output facet (3) removes most of the output modulation as there is very little reflection from the slot in this direction while angling of both facets (4) removes the modulation as now very little reflection in both directions from the slot occurs and we return to an almost FP output. These different schemes for angling of the slot interface are modelled and shown in figure 5.15 and figure 5.16 below.
Figure 5.15. Modelled output from a laser diodes with a single slot with straight interfaces (-)(1 above) and with interface closest to output facet angled (-)(3 above)

Figure 5.16. Modelled output from a laser diodes with a single slot with interface farthest from the output facet angled (-)(2 above) and with both interfaces angled (-)(4 above)
Experimental investigation of single slot lasers

Single slot Spectra

InGaAlAs laser diodes with one etched slot like that shown schematically in figure 5.2 was set up on a copper mount with a thermal control held at a constant 20°C while a current source is used to electrically pump the diode. The optical output is coupled to a lensed fibre with coupling efficiency of around 30% which is split 99/1 with 1% going to a photodetector to monitor coupling and 99% displayed on an optical spectrum analyser (OSA). The experimental set up is shown below in figure 5.17.

![Single slot ridge waveguide laser](image)

Figure 5.17 single slot experimental set up, OSA – optical spectrum analyser, PD – Photodetector.

The laser diode is biased to just below threshold in order to observe most of the slot characteristics. To find threshold an (Power-Current) LI curve is measured. This is measured by increasing the injection current and recording the coupled output power on the PD as in the setup above. The second derivative of the LI curve gives the points of inflection of which the first is the threshold current ($I_{th}$). The recorded LI curve for a single slot with both interfaces straight is shown below in figure 5.18.
The single slot laser diode is then biased at just below threshold ($I = 14$ mA) and the amplified spontaneous emission spectrum (ASE) is recorded on the OSA. The recorded ASE for a straight interfaced slot and for a slot with both interfaces angled at 10°, 100 μm from the front facet with an overall cavity length of 350 μm is shown in figure 5.19 below.
Figure 5.20 shows a similar laser diode however only one slot interface is angled. The influence of the etched slot can be seen as a periodic modulation of the peak height in both the straight and 2nd interface angled laser diodes, in the 1st interface angled laser the influence is less, however, it is non zero. This shows that even with angled slots there are still some reflection from the interfaces as an 8-10° angle still produces some feedback. By performing a Fourier transform (FT) on the ASE spectrum as described in chapter 4, the position of the slots in the laser cavity can be determined provided the facet reflectivity and cavity length are known. The amplitude reflection and transmission can also be determined by this method as described here. The net mode gain calculated from the Fourier series expansion (FSE) method as described in chapter 4 also is shown below in figure 5.21 where the influence of the slot is clearly seen as a modulation of the gain spectrum.
As seen in the previous section the presence of the slot in the laser cavity produces a modulation of the ASE spectrum. As this modulation is periodic with wavelength a Fourier transform (FT) can be performed on the ASE spectrum to determine some of the slots characteristics. The FT \( I(z) \) is found for the entire ASE spectrum including a window function to reduce the error at the edges of the transform as described in [10, 11], as

\[
I(z) = \int_{-\infty}^{\infty} I(\beta) \exp(-i2\pi\beta z) d\beta
\]

(5.25)

where \( z \) is the distance along the laser cavity in the propagation direction, and \( \beta \) is the wavenumber. This spectrum consists of a series of peaks in the wavenumber domain relating to the reflection centres in the cavity and associated harmonics. Therefore the main peaks seen in the FT spectrum arise from the cleaved facets and from these the normalised length of the cavity can be determined. Other smaller peaks are also seen representing the slot and harmonics of the slot. The amplitude of these smaller peaks are related to the amplitude of the reflectivity of the slot interfaces, and as such different slot geometries will have different FT spectra. The FT spectra for the four
different slot types described above (both interfaces straight, both slot interfaces angled, 2\textsuperscript{nd} interface angled and 1\textsuperscript{st} interface angled) are shown below in figure 5.22 with figure 5.23 showing a close up of the first normalised cavity length FT spectra.

Figure 5.22. Fourier Transformed spectra for different types of single slot laser diodes

Figure 5.23. A close up of the first cavity length normalised Fourier Transform spectra for four different slot types.
As can be seen in figure 5.23 the largest slot reflectivity is observed with the slots with both interfaces straight while the least is observed with both interfaces angled which compared well with the theory presented above. Therefore if we require a large modulation of the spectrum straight slots are used. The angled slots are used to remove the dependence of one cleaved facet on the position of the slot in the cavity and if particular longitudinal modes are required to be suppressed then angled slots may be used.

There have been many schemes to measure the reflection amplitude and transmission amplitude for a slot (defect) inside a laser cavity [7, 12, 13]. The extraction based on the Fourier transform (FT) method [5, 10, 14, 15] is an elegant method to determine these parameters. However this method is at present based on the power transmission spectrum which requires the laser diode to be mounted for access to both facets. As the amplified spontaneous emission (ASE) is measured with access to just one facet a method based on the ASE would simplify this measurement greatly. There is no difference between the power transmission spectrum and ASE when using the FT method to measure the optical gain, however there is a slight difference when the ASE is used to measure the reflection and transmission from an inter-cavity defect. Figure 5.24 shows a schematic of a laser ridge with a slot etched into it a distance $d_1$ from the left facet (output facet) and $d_2$ from the right facet. From this we see that the cavity is separated into two sub-cavities due to this slot. The slot has a length in the propagation direction of $\delta$.

![Figure 5.24. Schematic of a Fabry-Perot (FP) laser with a reflective defect (slot).](image)

The transmission ($t_s$) and reflection ($r_s$) are assumed to be independent of the direction of the incident optical field. The facets are cleaved with amplitude reflection ($r_f$) of 0.55. The measured ASE from the left facet can be described as
\[ I = I_1 + I_2 \]  

(5.26)

where \( I_1 \) and \( I_2 \) are the ASE from cavities 1 and 2.

\[
I_i = S|\eta_i|^2 \frac{\exp(gd_i) - 1}{g} \frac{1 + |r_i|^2 \exp(gd_i)}{|1 - r_lr_i \exp(gd_i \exp(-j2\beta d_i))|^2}
\]

(5.27)

where this is obtained in similar fashion to the earlier equations for amplitude reflection and transmission from a single slot laser. Here \( S \) is the spontaneous emission coupled into the waveguide mode, \( g \) is the net modal gain, \( r_{li} \) and \( r_{ri} \) are the left and right reflection coefficients as seen by the \( i^{th} \) section, \( t_{li} \) is the left transmission coefficient of the \( i^{th} \) section and \( \beta \) is the complex propagation constant as defined earlier. Assuming the reflection from the slot is weak, i.e. the laser is not described as having two cavities like a coupled cavity laser but just a small reflective defect internally, a first order approximation can be used

\[
I \approx (I_1^0 + I_2^0) + (I_1^1 + I_2^1)
\]

(5.28)

where the superscript refers to the order to which \( r_i \) is proportional. In order to find expressions for the first order approximations the following are used

\[
t_{li} = \sqrt{1 - r_f} = t_f
\]

(5.29)

\[
r_{li} = r_f
\]

(5.30)

\[
r_{l1} \approx r_s + t_s r_f \exp(-j2\beta d_2) \exp(gd_2) \left[ 1 + r_f \exp(-j2\beta d_2) \exp(gd_2) \right]
\]

(5.31)

\[
t_{l2} \approx t_1 t_f + \exp(-j\beta d_1) \exp(gd_1/2) \left[ 1 + r_f \exp(-j2\beta d_1) \exp(gd_1) \right]
\]

(5.32)

\[
r_{l1} \approx r_s + t_s^2 r_f \exp(-j2\beta d_1) \exp(gd_1) \left[ 1 + r_f \exp(-j2\beta d_1) \exp(gd_1) \right]
\]

(5.33)

\[
r_{r2} = r_f
\]

(5.34)

the phase shift due to \( r_f \) is assumed to be zero, therefore \( r_f \) is real. These equations are similar to those used to calculated the reflection and transmission using the SMM as described for a Fabry-Pérot laser in chapter 3 and a single slot laser from (5.8) to
The total transmission including the phase shift introduced by the defect is given by \( t_s \) which is

\[
t_s = \exp(- j \beta \delta) \tau
\]

where \( \tau \) is the transmission amplitude. From (5.29) to (5.34) the first order approximation is given by

\[
I_i \approx I_i^0 \left[ 1 + \left( \ln I_i \right)^\dagger \right] = I_i^0 (1 + P_i)
\]

where

\[
P_i = P_2 + \tilde{Q}_1
\]

where

\[
P_2 = \frac{\rho_i \rho_f \exp(- j 2 \beta d_1)}{1 - \exp(- j 2 \beta L)} r_s + \text{c.c.}
\]

where \( b \) is the round trip gain \( (b = \rho_f \rho_i \exp(\gamma d_1 + \gamma d_2)) \), \( L \) is the total cavity length \( (L = d_1 + d_2 + \delta) \), \( \rho_1 = \exp(\gamma d_1) \), \( \rho_2 = \exp(\gamma d_2) \), \( Q_1 \) is given below and c.c. refers to the complex conjugate. Therefore the total ASE from (5.36) is

\[
I \approx \left( I_i^0 + I_i^0 \right) (1 + P_2 + \frac{I_i^0}{I_i^0} \tilde{Q}_1) = \left( I_i^0 + I_i^0 \right) (1 + P_2 + \tilde{Q}_1)
\]

where

\[
I_i^0 = \frac{1 + b \rho_2 \tau^2}{g} \left| 1 - b \exp(- j 2 \beta L) \right|^2
\]

\[
I_i^0 = \frac{1 + r_i^2 \rho_2}{g} \left| 1 - b \exp(- j 2 \beta L) \right|^2
\]

and

\[
\tilde{Q}_1 = \frac{b r_i^{-1} \exp(\gamma 2 \beta (d_2 + \delta)) - \rho_2 r_f \exp(- j 2 \beta d_2)}{\Xi} r_s + \text{c.c.}
\]
where

$$\Xi = 1 + b\rho_2\tau^2 + \rho_1\tau^2\left(1 + r_1^2\rho_2\right)\left(\rho_2 - 1\right)/(\rho_1 - 1)$$  \hspace{1cm} (5.43)

The $\hat{Q}_1$ term is the difference between the power transmission and ASE spectra as this term does not appear in the power transmission spectrum description. The FT of the ASE spectrum as described in chapter 4 is

$$\tilde{I}(z) = \int I(k)\exp(-jkz)dz$$  \hspace{1cm} (5.44)

will consist of a series of peaks due to feedback from the facets and the slot interfaces. Here we concentrate on the peaks located at $\zeta = 0$, $2n_{eff}L$, $2n_{eff}d_1$, $2n_{eff}d_2$, $2n_{eff}(L+d_1)$ and $2n_{eff}(L+d_2)$, which when normalised to $2n_{eff}L$ gives $\zeta = 0$, $1$, $\eta_1$, $\eta_2$, $(1 + \eta_1)$ and $(1 + \eta_2)$ where $\eta_1 = d_1/L$ and $\eta_2 = d_2/L$. By decomposing the ASE intensity under the first order approximation (5.39) the following can be found:

$$t_0 = \frac{St_0^2\left[\left(\rho_1 - 1\right)g^{-1}(1 + b\rho_2\tau^2) + \tau^2\rho_1\left(\rho_2 - 1\right)g^{-1}(1 + r_1^2\rho_2)\right]}{1 - b^2}$$  \hspace{1cm} (5.45)

$$t_1 = t_0b\exp(-j2\beta L)$$  \hspace{1cm} (5.46)

$$t_{\eta_1} = \left[(A_{\eta_1} + C_{\eta_1})u + (B_{\eta_1} + D_{\eta_1})\exp(-j2\beta\delta)v\right]\exp(-j2\beta d_1)$$  \hspace{1cm} (5.47)

$$t_{\eta_2} = \left[(A_{\eta_2} + C_{\eta_2})\exp(-j2\beta\delta)u + (B_{\eta_2} + D_{\eta_2})\exp(-j2\beta d_2)\right]\exp(-j2\beta d_2)$$  \hspace{1cm} (5.48)

$$t_{1+\eta_1} = \left[(A_{1+\eta_1} + C_{1+\eta_1})u + (B_{1+\eta_1} + D_{1+\eta_1})\exp(-j2\beta\delta)v\right]\exp(-j2\beta(L + d_1))$$  \hspace{1cm} (5.49)

$$t_{1+\eta_2} = \left[(A_{1+\eta_2} + C_{1+\eta_2})\exp(-j2\beta\delta)u + (B_{1+\eta_2} + D_{1+\eta_2})\exp(-j2\beta(L + d_2))\right]\exp(-j2\beta(L + d_2))$$  \hspace{1cm} (5.50)

where

$$u = r_s\tau^{-2\eta_1}$$  \hspace{1cm} (5.51)

and

$$v = r_s\tau^{-2\eta_2}$$  \hspace{1cm} (5.52)

From (5.45) to (5.50) the following are used
\[ A_{\eta_1} = t_0 \frac{b^{\eta_1} r_f^{1-2\eta_1}}{1 - b^2}, \quad A_{\eta_2} = b A_{\eta_1}, \quad A_{i+\eta_1} = b(2 - b^2)A_{\eta_1}, \quad A_{i+\eta_2} = b^2 A_{\eta_1} \quad (5.53) \]

\[ B_{\eta_1} = b B_{\eta_2}, \quad B_{\eta_2} = t_0 \frac{b^{\eta_2} r_f^{1-2\eta_2}}{1 - b^2}, \quad B_{i+\eta_1} = b^2 B_{\eta_2}, \quad B_{i+\eta_2} = b(2 - b^2)B_{\eta_2} \quad (5.54) \]

\[ C_{\eta_1} = b C_{\eta_2}, \quad C_{\eta_2} = t_0 \frac{b r_f^{-1} r_f^{2\eta_1}}{\Xi}, \quad C_{i+\eta_1} = b^2 C_{\eta_2}, \quad C_{i+\eta_2} = b C_{\eta_2} \quad (5.55) \]

\[ D_{\eta_1} = b D_{\eta_2}, \quad D_{\eta_2} = t_0 \frac{b^{\eta_2} r_f^{1-2\eta_2}}{\Xi}, \quad D_{i+\eta_1} = b^2 D_{\eta_2}, \quad D_{i+\eta_2} = b D_{\eta_2} \quad (5.56) \]

where in the above the following relations were used

\[ \rho_1 = b^{\eta_1} r_f^{2\eta_1}, \quad \rho_2 = b^{\eta_2} r_f^{2\eta_2} \quad (5.57) \]

therefore

\[ \Xi = 1 + b^{1+\eta_2} r_f^{2-2\eta_2} r_f^{2-2\eta_2} + (b + b^{\eta_1} r_f^{2-2\eta_1} r_f^{2-2\eta_1}) \frac{b^{\eta_2} r_f^{2-2\eta_2} r_f^{2-2\eta_2}}{b^{\eta_2} r_f^{2-2\eta_2} r_f^{2-2\eta_2}} - 1 \quad (5.58) \]

where the approximations \( d_1/d_2 \approx d_1/L \equiv \eta_1 \) and \( d_2/(d_1+d_2) \approx d_2/L \equiv \eta_2 \) have been used. The C and D terms are the difference between using the ASE spectrum and the power reflection spectrum and come from Q1. Taking the inverse FT of the peak at \( \zeta = 0 \) (called the 0th peak) the spectrum of \( u_0 \) can be found. Taking the inverse FT of the peak at \( \zeta = 1 \) (called the 1st peak) the spectrum of \( u_1 \) can be found. The ratio of \( u_0/u_1 \) gives the round trip gain spectrum (b). This is the same as the FT method to calculate the round trip gain from chapter 4. The values of \( u_0 \) and \( u_1 \) are easy to find by this method however the values for the smaller slot peaks in the FT spectrum are just above the noise floor and as such are difficult to determine by this method accurately. In order to find these more accurately first extract \( u_0 \) and the b spectrum, then extract the values for \( \eta_1 \) and \( \eta_2 \) and the Fourier amplitude maxima at \( \zeta = \eta_1, \eta_2, (1 + \eta_1) \) and \( (1 + \eta_2) \), then from theoretical estimations for \( r_s, \tau \) and \( \delta \), scan them in a suitable range and calculate the theoretical Fourier maxima at these minor peak positions using equations (5.45) through (5.56) and compare to the Fourier amplitude maximums.
obtained above. The recorded ASE for a single slot laser with straight interfaces and a cavity length of 350 μm at 6 mA injection current is shown below in figure 5.25.

![ASE spectrum](image)

**Figure 5.25.** Recorded ASE spectrum for single slot laser at 6 mA injection current.

Using this method the following values for a single slot laser diode with straight interfaces were obtained, \( r_s = 0.07 \), \( t = 0.910 \) and \( \delta = 1.055 \) μm. These values are intuitive as the reflectivity should be close to 0.1 in the ideal case, however in practice the interface will not be entirely smooth therefore the reflectivity will be lower. The slot was fabricated to be 1 μm so this value of 1.055 μm is very close.

**Conclusion**

The single slots described here are clearly seen not to produce enough mode selectivity for single longitudinal mode laser operation. However the reflectivity and position in the cavity can be characterised as shown above. In the next chapter the ideas in this chapter are expanded and a discussion of multiple slots in a laser cavity with different slot spacing to employ the Vernier effect for tuning the mirror loss profile for tunable single mode lasing is provided.
References


Chapter 6 – Tunable Laser Diodes

Introduction
Tunable lasers diodes (TLD) have been used in optical networks for some time now starting with devices with small wavelength coverage and moving towards full band coverage. Tunable lasers have a number of advantages over fixed wavelength DBR type lasers not least in dynamic networks with wavelength reconfigurability where any channel can be added or dropped independently. TLD will also play an important part in wavelength converters and wavelength routing where optical-electronic-optical (OEO) converters will detect any input channel and convert to any output channel. TLD also reduce inventory costs significantly when used as sparing backups to fixed wavelength lasers. New approaches to data transmission such as coherent WDM (CoWDM [1]) require discrete tuning between particular wavelength channels on a grid. There is additionally an urgent need to integrate semiconductor lasers with other optical components such as amplifiers, modulators and detectors [2-5] in order to reduce chip cost, system size and complexity. Tunable lasers are also needed in other important markets such as trace gas detection for environmental emission motoring [6]. For sparing applications in dense wavelength division multiplexing systems TLD’s will have to meet the same specifications as fixed wavelength lasers i.e. optical power, wavelength accuracy, relative intensity noise (RIN), side-mode suppression ratio (SMSR) another important additional requirement for tunable lasers is that the laser has to be optically isolated from the network during tuning in order to avoid polluting the network with light emitted during the switching, however for most if not all current and near future applications of TLD there is no demand for fast (ns) wavelength switching.

Laser operation requires optical feedback which is conventionally obtained in a semiconductor Fabry-Pérot laser by cleaving the ends of the laser waveguide along either (011) or (01-1) crystallographic planes to form two semi-reflecting facets. However, due to the need for cleavage, it is difficult to integrate these lasers with other optical components on a single chip. Distributed-Bragg-reflector (DBR) lasers and distributed feedback (DFB) lasers which employ a series of small refractive index
perturbations to provide feedback, do not rely on cleaved facets and therefore can be integrated with optical amplifiers and modulators [4, 5]. However, complex processing with multiple epitaxial growth stages is required for fabricating these lasers. Another method to obtain feedback is to etch a facet. However, this approach is limited by difficulties in the smoothness and verticality of the etched facet particularly for structures based on InP materials.

Previously it was shown that by introducing a shallow slot into the active ridge waveguide of a laser, the longitudinal modes of the Fabry-Pérot (FP) cavity were perturbed according to the position of the slot with respect to the cleaved facets [7-9]. By judicious placement of a sequence of low-loss slots with respect to the facets pre-selected FP modes could be significantly enhanced leading to robust single frequency lasing with wide temperature stability [10, 11] as well as tuning with fast switching characteristics [12]. More recently, we have characterized the properties of slots which are etched more deeply namely to the depth of, but not through, the core waveguide containing the quantum wells [13]. In that case, the reflection of each slot is of the order of ~1% with transmission of ~80% and the slot will strongly perturb the mode spectrum of the FP cavity by creating sub-cavities. The loss introduced by the presence of the slot is compensated by gain in the laser. An array of such slots can provide the necessary reflectivity for the laser operation independent of a cleaved facet where the gain between the slots compensates for the slot loss producing an active slotted mirror region. Such a mirror has been used in conjunction with a cleaved facet permitting the integration of a photodetector with the laser [14].

In this chapter, we use reflective slots and the associated mirrors as the platform technology for the realization of a facetless laser which can be tuned using differential current injection into different longitudinal sections. Furthermore the integration of the tunable laser with an optical amplifier is also demonstrated. The electrical isolation between the different sections is made possible by the etched slots. The slots are realized by conventional photolithography and dry etching during the definition of the waveguide. As the technology is based on a generic single epitaxial growth stage and upon standard laser processing steps, it is compatible with implementation in a foundry.

This chapter begins by describing a single laser section with many slots etched into the laser cavity. This is shown to provide single mode lasing however the tunability is small. This idea is expanded to include another section with no slots to
improve the tunability, however the increase is small. The next part describes a three section laser with large wavelength coverage and finally a three section laser with an integrated semiconductor optical amplifier is described and characterised.

All the simulations in this chapter use the following laser characteristics:

1. The optical gain is wavelength dependent and is from a FP laser diode which is not carrier density dependent that is it is set at a particular value per cm and is not changed.
2. The effective refractive index does not change with slot number
3. All facets have amplitude reflection ($r$) of 0.55 (power reflection = 0.3) and have no scattering loss that is the facet amplitude transmission ($t = \sqrt{1-r^2}$).
4. The change in carrier density effects the refractive index only by the free carrier plasma effect.
5. The device temperature is not taken into account.
6. The waveguide to slot power reflectivity is 0.014, power transmission is 0.972 and power loss is 0.247 as described in [15]. The slot to waveguide power reflectivity is assumed zero as it is much smaller.

**Single section slotted laser**

In this section a single section slotted laser with slots etched into the ridge of the waveguide down to the active region is introduced and characterised. This single section laser will form the basis for our three section tunable laser when combined with another similar section and a gain section which provides most of the optical gain. These slotted sections are termed “active slotted mirrors” as there is optical loss from each individual slot and therefore the reflection from a group of slots will saturate quickly if the slot loss is not effectively compensated. In the design presented here, the mirror regions are also actively pumped which provides the necessary gain under current injection to compensate for the loss introduced by the slots.

Firstly the scattering matrix method (SMM) as described in chapter 3 and used in chapter 5 to model single slot lasers is used to determine the reflection, transmission, mirror loss and full width at half maximum (FWHM) of the reflection bandwidth profile with wavelength for a number of different slots at a particular slot spacing and gain conditions. Figure 6.1 below depicts the single section laser that is described below.
1 = Upper electrically conductive layer, 2 = Ridge of the waveguide, 3 = Upper cladding layer, 4 = Active region, 5 = Lower cladding layer, 6 = Lower electrically conductive layer, 7 = Etched slot.

Figure 6.1. Schematic of slotted single section laser diode.

A slot spacing of ~ 100 µm is chosen as this provides a reflection spectrum with super-mode peaks at ~ 400 GHz (3.2 nm) spacing which is similar to that used on the ITU grid. The free spectral range of the super-mode peaks is determined by the slot spacing through the following formula

\[ FSR = \frac{\lambda^2}{2n_g L} \]  

(6.1)

where \( n_g \) is the group effective index, \( L \) is the slot spacing and \( \lambda \) is the nominal wavelength. Starting from the SMM to describe a single slot with both slot interfaces straight etched into a medium that has gain and with anti-reflective (AR) coated facets, the reflection amplitude (\( S_{s11} \)) is described simply as

\[ S_{s11} = r_4 + t_4 S_{s11}(-t_4) \exp(-2i\beta L) \]

(6.2)

where \( r_4 \) and \( t_4 \) are the reflection and transmission from and through the front facet and \( S_{s11} \) is the effective reflection from the slot and back region, this is identical to equation 5.19 in chapter 5. This equation can be expanded to include more slot and gain regions if the facet value in 6.2 is changed to a slot to waveguide value. Then a new equation can be created describing a laser cavity with two slots i.e.
This method of modelling can be repeated up to the required number of slots is reached. The amplitude transmission for a particular number of etched slots is found by the same method starting from equation 5.20 in chapter 5. Once the amplitude reflection and transmission are found, the mirror loss spectrum is easily determined from

$$\frac{1}{2L} \ln \left( \frac{1}{R^2} \right)$$

(6.4)

where $L$ is the laser cavity length and $R$ is the power reflectivity which can be found from the amplitude reflectivity as

$$R = \text{abs} \left( (S_{\text{total}11})^2 \right)$$

(6.5)

The simulated power reflectivity as a function of wavelength for different numbers of slots from the above method is shown below in figure 6.2.
In figure 6.2 the effective index is unchanged as the slot number is increased, therefore the wavelength peak positions do not change with slot number. From figure 6.2 as the number of slots is increased the reflection at wavelengths determined by the slot spacing is also increased. This dependence of the maximum power reflection on slot number is shown below in figure 6.3, an exponential increase is observed, therefore more slots will provide better single mode operation however increasing the slot number also increases the length of the laser so a compromise of nine slots is used.

![Graph showing maximum power reflection versus slot number.](image)

**Figure 6.3.** Maximum power reflection versus slot number.

As the mirror loss spectrum is inversely proportional to the reflection spectrum, the wavelength determined by these peaks will reach threshold first and lase at these positions provided the round trip loss is overcome by the gain between the slots. The mirror loss spectrum for a nine slot laser with AR coated facets and a slot spacing of 100 µm is shown below in figure 6.3. The mirror loss in this simulation is lowest at ~1550 nm which means the round trip gain will be largest here and this wavelength will reach threshold first and lasing will occur at this wavelength.
The longitudinal (cavity) mode spacing is determined by the overall cavity length and lasing occurs where a cavity mode overlaps with a slot reflection peak at the wavelength of highest gain. These reflection peaks are called super-modes. The number of slots directly affects the linewidth of the reflection spectrum super-modes and as shown in figure 6.4 below a larger number of slots provides the narrowest super-mode peaks.

Figure 6.3. Mirror loss spectrum at a peak round trip gain of 0 cm⁻¹.

Figure 6.4. Full width half maximum (FWHM) and FWHM normalised to FSR, of super-mode peaks versus slot number.
As the number of slots increases the linewidth of the reflection peaks decreases, therefore less cavity modes are covered by each super-mode meaning less cavity mode jumps are seen in the laser output spectrum. Increasing the number of slots also increases the length of the laser. Therefore a balance needs to be found between the reflection spectrum bandwidth and the laser length as it is better to keep the laser length as small as possible for integration on photonic chips. As the entire structure is active, the loss introduced by the slots needs to be compensated by the optical gain between the slots. This can be simulated simply by changing the term containing the gain in the SMM equations. In practice this is changed by increasing or decreasing the imaginary part of the complex propagation constant i.e.

\[ \beta_{im} = \frac{g}{2} \]  

(6.6)

where \( g \) is the net mode optical gain. The net mode optical gain used in these simulations is experimentally determined from a Fabry-Pérot laser diode by the Fourier series expansion as described in chapter 4. Figure 6.5 shows the variation of the reflection spectrum peak mode linewidth as the net mode gain is increased from a value of -30 cm\(^{-1}\) to 30 cm\(^{-1}\). This simulation shows that as the gain increases, the linewidth of the reflection spectrum decreases. This implies that the laser will have better single mode operation as the optical gain is increased.
As described in chapter 5 very little reflection is observed from the slot to waveguide interface compared to the waveguide to slot interface and as such the slot can be described as a discontinuity in the laser cavity and therefore a simpler model can be used to describe this situation which is described in detail below.

As shown schematically in figure 6.6 below the slot is assumed to be a one dimensional discontinuity inserted in the laser cavity as most of the reflection is from the front slot interface and the slot width has a minimal effect on the reflection as shown in chapter 5 in figure 5.6.

\[ r_s \text{ and } t_s \text{ refer to the slot reflectivity and slot transmission respectively. The reflectivity of the section is described by } \lambda_i \text{ where } i \text{ is the slot number. The above schematic shows how to calculate the reflection and transmission for six slots but as shown below this is just a converging series.} \]

\[ \lambda_1 \text{ is the reflectivity from one slot and is given by } r_s. \]

\[ \lambda_2 \text{ is the reflectivity from two slots and is given by } r_s t_s^2 \exp(-2i\beta L), \text{ where } \beta \text{ is the complex propagation constant and } t_s \text{ is squared as there is a transmission term from both forward and backward (left and right) travelling waves. The term in the exponent describes the medium in which the light is travelling which includes the length and} \]

Figure 6.6. Illustration of slot reflection and transmission calculation.
the loss/gain terms. The factor of 2 again refers to both forward and backward travelling light. The complex propagation constant is defined in terms of

$$\beta = \beta_{re} + i\beta_i = \frac{2m n}{\lambda} + \frac{i g - \alpha_i}{2}$$  \hspace{1cm} (6.7)

where \(n\) is the refractive index, \(\lambda\) is the wavelength, \(g\) is the optical gain and \(\alpha_i\) is the internal cavity loss. The 2 in the quotient in the last term is to reduce this term to amplitude as both \(g\) and \(\alpha_i\) relate to power.

The reflectivity from three such slots is given by

$$\gamma_3 = r_s t_s^4 \exp(-4i\beta L)$$  \hspace{1cm} (6.8)

and for four slots the reflectivity is given by

$$\gamma_4 = r_s t_s^6 \exp(-6i\beta L)$$  \hspace{1cm} (6.9)

This gives a total reflectivity from \(N\) slots as

$$\gamma_{total} = \gamma_1 + \gamma_2 + \gamma_3 + \gamma_4 =$$

$$r_s + r_s t_s^2 \exp(-2i\beta L) + r_s t_s^4 \exp(-4i\beta L) + r_s t_s^6 \exp(-6i\beta L)$$  \hspace{1cm} (6.10)

As can be seen this can be described as a series for the total reflectivity from \(N\) slots by letting

$$X = t_s^2 \exp(-2i\beta L)$$  \hspace{1cm} (6.11)

therefore the total reflectivity can be described as

$$\gamma_{total} = r_s \left(1 + X + X^2 + X^3 + \ldots + X^N\right)$$  \hspace{1cm} (6.12)

which in terms of known variables can be described as

$$r = r_s \frac{1 - \left(t_s^2 \exp(-2i\beta L)\right)^N}{1 - t_s^2 \exp(-2i\beta L)}$$  \hspace{1cm} (6.13)

Similarly the total transmission can be described as
Using this method the power reflectivity from a laser with anti-reflective (AR) coated facets, nine slots and an inter-slot spacing of 107.3 μm is displayed in figure 6.7. A slot spacing 107.3 μm gives a FSR of 3.2 nm from (6.1) which corresponds to a peak spacing of 400GHz. The power reflection and power transmission is related to the amplitude reflection and amplitude transmission through

\[ R = \text{abs}(r^2) \]  

(6.15)

and

\[ T = \text{abs}(t^2) \]  

(6.16)

where abs is the absolute value.

As can be seen this approximate method produces a cleaner spectrum compared to figure 6.2 above as the reflections from the slot to waveguide side of the slot are
discarded as it is easier to implement in this form and will be again used in the following sections to depict tunable laser diodes based on this slotted structure. Again as before in figure 6.2, the effective index is unchanged as the slot number is increased, therefore the wavelength peak positions do not change with slot number. The mirror loss spectrum calculated by this method is shown in figure 6.8 below. Again the gain used in these simulations is found from experimentally characterising an un-slotted Fabry-Pérot laser diode using the Fourier series expansion to calculate the optical gain in (6.7) above.

![Figure 6.8. Mirror loss versus wavelength for 9 slotted device.](image)

As described in chapter 2 the refractive index is dependent on the injected carrier density through the free-carrier plasma effect and will also be influenced by bandgap shrinkage and band filling effects. A combination of these effects can produce up to a change in refractive index of -0.04 [16], which corresponds to a maximum theoretical tuning range -8 nm, where the minus sign suggests that the tuning is to the short wavelength end. The effective refractive index of the laser is determined from the effective index method described in [17]. The dependency of the real part of the effective refractive index on the carrier density in the laser cavity is given by (6.17) below.
\[ \Delta n' = -\frac{e^2 \lambda^2}{8\pi^2 c^2 n\varepsilon_0} \left( \frac{1}{m_e} + \frac{1}{m_h} \right) N \]  

(6.17)

where \( e \) is the electronic charge, \( \lambda \) is the wavelength, \( \varepsilon_0 \) is the free space permittivity, \( c \) is the speed of light in vacuum, \( n \) is the effective refractive index, \( m_e \) is the injected electron effective mass, \( m_h \) is the hole effective hole mass and \( N \) is the injected carrier density. Using this formula and (6.12) the reflectivity spectrum and mirror loss versus wavelength for different effective refractive indices determined by the injected carrier density can be found and are displayed in figure 6.9 and 6.10.

![Reflection spectra for different carrier densities](image)

Figure 6.9. Reflection spectra for different carrier densities
Figure 6.10. Mirror loss spectra for different carrier densities

Figure 6.11. Effective refractive index and Wavelength versus carrier density. (large super mode hops are observed)

Figure 6.11 shows the refractive index and maximum reflection wavelength versus carrier density for the laser structure. The refractive index decreases as the carrier
density increase giving a blue shift of wavelength to higher energies. The jumps in figure 6.11 are referred to as mode hops and occur as the different modes line up with the gain peak. These mode hops decrease the overall continuous tuning of the laser diode unless the gain curve can also be tuned simultaneously.

Looking at one mode and recording the wavelength as the refractive index is changed as in figure 6.12 we find a maximum continuous tuning of 3.11 nm neglecting gain changes due to the imaginary part of the refractive index changing. The continuous wavelength dependence on refractive index is 1 nm ~ per 0.003 (0.6%) refractive index change.

![Figure 6.12. Wavelength change with refractive index change with a refractive index change of 0.00231 for 1 nm wavelength change.](image)

**Two section slotted laser simulations**

This single section slotted design can be extended to include extra sections to provide more gain or other mirror reflectivity spectra by using extra slotted sections to provide additional tunability. Including a second section with no slots will increase the gain in the overall laser and both sections can be electrically isolated by a slot with a contact discontinuity at the slot position. This allows carriers to be independently injected into each section using two current sources, the slotted section can be used for tuning while the un-slotted section can provide most of the optical gain for lasing. However
due to the large optical loss associated with the slots the slotted section is active to compensate for this loss. The simulated reflection spectrum for the laser shown schematically in figure 6.13 is shown in figure 6.14.

![Two section laser schematic](image)

Figure 6.13. Two section laser schematic.

![Reflection spectrum](image)

Figure 6.14. Two section reflection spectrum (one slotted section and one un-slotted section).

Figure 6.14 shows that the two section laser reflection spectrum shows a very clear influence of the extended cavity length through the presence of clearly visible cavity modes. Looking at these cavity modes and determining the cavity length from the cavity mode spacing by (6.18) shows that the effective optical length of the laser is
where \( L \) is the cavity length, \( n_g \) is the group index, \( \lambda \) is the nominal wavelength and \( \Delta \lambda \) is the cavity mode spacing. By changing the carrier density in the slotted region the maximum reflection wavelength can be tuned similar to that shown in figure 6.9, this is shown in figure 6.15. The minimum mirror loss wavelength is influenced by the super modes jumps, the gain curve and now additionally by the cavity mode positions relative to the gain and super modes positions. As the section is tuned small jumps are observed as the same super mode is lasing however different cavity modes are lining up with the super mode.

![Figure 6.15. Refractive index and wavelength versus carrier density for two section laser. (small cavity mode hops and large super mode hops are observed)](image)

**Two section slotted laser experimental results**

A two section laser as described by figure 6.13 was realised using the same fabrication steps as for a standard ridge waveguide laser and will be described in more detail later. The laser characterisation set up is shown in figure 6.16 below.
Two currents sources are used to independently inject current into each section of the laser diode. The isolation between sections is provided by the slot and contact discontinuity. Some carrier leakage across this isolation slot will occur and is discussed further later. The photodiode is used to record the coupled output power to determine if the coupling efficiency is stable. The LI (power current) curve which measures the coupled output power versus injected current was measured and threshold was determined to be 80 mA in the front section and ~ 30 mA in the slotted section. The front section was kept at a constant 80 mA in the following measurements and the temperature was kept at 20 °C by a TE cooler. The amplified spontaneous emission (ASE) spectrum was recorded at a mirror section current of 23 mA and is displayed in figure 6.17 below with inset of the power current curve for a mirror section injection current of 23 mA.
A large modulation of the ASE is seen due to the many etched slots in the laser mirror section. The Fourier transformed spectrum is shown in figure 6.18 below and the slot positions are seen along the laser cavity with their harmonics.
This type of laser can be shown to operate as a single mode laser, however as the injected current is changed the wavelength will change as different super modes satisfy the threshold condition and the output wavelength can shift to different wavelengths similar to that shown in figure 6.15 above.

Three section slotted laser simulations

Nine slots front section and five slots back section.

The tuning range can be greatly expanded by removing the cleaved facet and including another wavelength dependent mirror loss section. This section is the same as the slotted section described above however the number of slots and slot spacing is altered slightly so the Vernier tuning mechanism introduced in chapter two can be employed. The first laser structure considered has a central gain section, a back active mirror section with 5 slots and a front mirror section with 9 slots. The slot spacing in the back mirror \( (d_b) \) is 108 \( \mu \text{m} \) and the front mirror slot spacing \( (d_f) \) is 97 \( \mu \text{m} \), the laser structure is shown schematically in figure 6.19 below.

As the laser mirror sections are independent the above technique to calculate the reflection spectra and mirror loss from each mirror section can be employed and therefore the total reflection, transmission and mirror loss spectra can be determined. In these calculations the gain section injection current is set above threshold and both mirror currents are increased linearly. The dependence of the gain in the mirror with changing injection currents is discarded to reduce complexity in the calculations. For
this reason the gain in the mirror sections is set to more than compensate for the loss due to the slot. The reflection spectra for both mirror sections are shown in figure 6.20 below. The mirror section with 5 slots shows much lower reflection spectra as shown in figure 6.3 as there is an exponential increase in power reflection with increasing slot number.

Figure 6.20. Simulated reflection spectra for both mirror sections showing super mode positions.

Tuning of this laser is observed by changing the injected current thereby changing the effective refractive in each section and using the Vernier effect to determine which super modes are overlapped and lase. The total power reflection \((R_{\text{total}})\) is determined from

\[
R_{\text{total}} = \left| r_t r_r \right|^2 = abs\left[ (r_t)^2 + (r_r)^2 + (2r_t r_r) \right]
\]

(6.19)

In all these simulation the dependence of the gain curve on the injected current is ignored. In practical laser diodes the gain curve will also shift slightly with injected carrier density and also the gain will increase (decrease) with increasing (decreasing) injected current, however the Vernier effect tuning is much larger than the gain curve wavelength dependence. The power reflection from (6.19) for back and front section injection current changes with the injection current in the other section held constant at 100 mA is shown in figure 6.22. As the injection current is increased in the mirror
section the super mode decreases in wavelength due to a change in real part of the refractive index as shown in (6.17) until another super mode enters a region with higher gain due to the fixed gain curve maximum.

![Graph showing supermode positions](image)

Figure 6.22. Back and front super-mode positions as the injected current is increased from 30 to 150 mA (red – front section injection current = 100 mA, blue – back section injection current = 100 mA.)

The reflection from the front section is larger than the reflection from the back section, therefore the front section reflection spectrum dictates the wavelength at which the maximum reflection occurs and therefore the lasing position. A maximum reflection wavelength map can be constructed for all the different injection current configurations. This map shows the wavelengths that can be accessed by tuning both currents simultaneously. The tuning map is shown below in figure 6.23 a total of ~10 nm quasi-continuous tuning can be accessed with this configuration of slots. By changing the injected current in each mirror sections from 30 mA to 150 mA, four super mode position are observed in the simulation at wavelengths ~1546 nm, 1549 nm, 1552 nm and 1555 nm as shown below in figure 6.23. As the other supermodes on the side of the gain curve line up the power reflection from these modes is still less than the power reflection from the reflection peaks from the front mirror around the gain peak and therefore the lasing stays at the gain peak.
Figure 6.23. Wavelength tuning map for nine and five slotted three section laser diode showing supermode positions depicted by the different colours.
Nine slots front section and nine slots back section.

Increasing the back mirror reflector slot number will greatly enhance the wavelength range over which the laser can tune. In the following section a similar laser to that described above is simulated however, both mirrors now have nine slots. The laser structure is shown schematically below in figure 6.24.

As each section has nine slots the gain introduced between the slots is similar for each mirror section and therefore the reflection spectra are comparable to each other. As one mirror section has a larger inter-slot spacing, this section has marginally higher gain as well as a lower FSR. The back section has 97 μm slot spacing giving a FSR of ~ 3.5 nm with group index of 3.5. The front section has 108 μm slot spacing giving a FSR of ~ 3.2 nm. Therefore the Vernier tuning mechanism is again used. Using equation (6.13) the amplitude reflection of each section can be calculated and through equation (6.15) the power reflection spectrum can be calculated. The gain in each section is again fixed and only the refractive index is changed through a change in the injection through equation (6.17). The power reflection spectrum for both mirrors at a particular injection current is shown in figure 6.25 below. As the back section has a smaller slot spacing, the gain between the slots will be less and the reflection spectrum from this mirror section will be less than that from the front mirror section.
The total power reflection spectrum at a particular injection current for both mirrors is obtained again from (6.19). The maximum wavelength reflection for each mirror section when the other section is held at 100 mA is shown in figure 6.26 below.

Figure 6.26. Back and front super-mode positions as the injected current is increased from 30 to 200 mA (red – front section injection current = 100 mA, blue – back section injection current = 100 mA.)
Tracking the maximum power reflection wavelength of the total reflection power (using 6.19) a wavelength map similar to that in figure 6.23 can be calculated for this laser, the wavelength map is shown in figure 6.27 below.

![Wavelength tuning map for nine front and nine back slotted three section laser diode.](image)

Figure 6.27. Wavelength tuning map for nine front and nine back slotted three section laser diode.

Eight distinct super mode positions can be seen with over 20 nm tuning from the figure which is a large improvement on the tuning seen from the nine and five laser from above. The same data is plotted below in figure 6.28 in a mesh plot where the super-mode islands are more clearly visible.
Three section slotted laser experimental results

Nine slots front section and five slots back section.

The tunable laser design described above was realised using the same fabrication steps as for a standard ridge waveguide laser. The laser epitaxial structure is a standard design employing an active region of 5 AlGaInAs quantum wells surrounded by InP n and p doped cladding regions. 2.5 μm wide ridge waveguides were formed by inductively coupled plasma etching using Cl₂/N₂ gas. The slots are etched simultaneously with the ridge to a depth just into the waveguide core. The sidewalls are passivated with SiO₂ and an opening is made to the top of the ridge where a patterned Ti/Pt/Au electron beam evaporated ohmic contact is formed by lift-off lithography. The etched slot is sufficient to isolate the different longitudinal sections of the device allowing independent current injection. Following thinning of the
substrate to 120 μm an Au/Ge/Ni/Au contact is evaporated on to the n-type substrate. The devices are cleaved to the desired lengths and a single layer antireflection coating applied to the facets. Quantum well intermixing (QWI) was employed during fabrication to change the wavelength from 1550 nm to 1500 nm. QWI allows the properties of a semiconductor to be altered after growth for example the bandgap. In this case the intermixing causes Al to diffuse into the quantum well and Ga out of it, modifying the quantum well shape and increasing its average bandgap which makes a passive region in the semiconductor material. The laser has nine slots in the front mirror section and five slots in the back mirror section.

Three current sources were used to independently inject current into the gain and two mirror sections of the laser. The experimental set-up is similar to that depicted in figure 6.16 except that three current sources are used. The device was mounted on a heat sink and held at a constant temperature of 20°C using a thermoelectric cooling unit. Figure 6.29 shows the maximum wavelength and SMSR versus the front injection current while the gain section and back section are kept at a constant 100 mA.

![Graph](image)

Figure 6.29. Output wavelength versus front section injection current with the back and gain sections held at a constant 100 mA.
The differences between the simulated and experimentally obtained wavelength change with injection current result from the absence of some physical phenomenon in the laser cavity these include, no change in the net mode gain as the injection current is changed in the mirror sections (as if the mirrors were passive), no spontaneous emission in the mirror sections and only the free carrier plasma effects taken into account for the changes in the refractive index in the mirrors as the injection current is changed. In real laser diodes the free carrier plasma effect is accompanied by band gap filling and shifts in the absorption edge of the semiconductor as well as thermal changes as the injection current changed. As these have been neglected in the simulations in this thesis there is a limit to these models used here.

For a complete characterisation the current in the front mirror section was changed from 250 mA to 0 in steps of 1 mA. The back mirror section injection current was changed from 100 mA to 0 mA in steps of 1 mA. The current is larger in the front section as this section is longer (back section length = 540 µm, front section length = 873 µm). The wavelength and peak power of the laser emission spectrum and the side-mode-suppression-ratio (SMSR) were recorded using an optical spectrum analyzer with a resolution bandwidth of 0.1 nm. These are mapped versus the injection current in each section in figures 6.30 (power), 6.31 (SMSR) and 6.33 (Output wavelength).

![Power versus mirror injection currents](image_url)

Figure 6.30. Coupled output power map versus both mirror section injection current.
As can be seen in figure 6.30 the power is dependent on the injection current and as one would expect as the current is increased the output power increases.

Figure 6.31. SMSR map versus both mirror section injection current.

An SMSR of at least over 25dB as required for the lasing to be deemed as single mode output. As can be seen from figures 6.31 and 6.32, there are areas where the SMSR is low however this usually occur at the boundaries of super-modes where super-mode hops occur.

Figure 6.32. Wavelength map versus both mirror section injection current.
Figure 6.32 is a mesh map in which it is easier to see the transitions from one wavelength to another.

Figure 6.33. Wavelength versus injection currents for both mirror section injection current.

Combining figures 6.31 and 6.32 the SMSR versus the wavelength over all injection currents can be found. Four super-modes around 1500 – 1515 nm show good SMSR, the power versus wavelength is shown in figure 6.35. Where the SMSR is large the power is also large showing that there is good single mode lasing at these wavelengths with a particular combination of injection currents.
Figure 6.34. SMSR versus wavelength for both mirror section injection current changes, each point in this plot represents a particular set of front and back section injection currents.

![Figure 6.34](image)

Figure 6.35. Power versus wavelength for both mirror section injection current changes, where again each point in this plot represents a particular set of front and back section injection currents.

The output spectrum shown in figure 6.36 below shows the four accessible super-modes accessible with this laser with the gain section at 100 mA.
Nine slots front section and nine slots back section.

The first three section slotted laser with nine slots in each section characterised here was the laser shown schematically in figure 6.24 with cleaved facets. This laser is designed to operate with a super-mode spacing of 400 GHz (~3.2 nm). The SMSR versus wavelength for this laser is shown below in figure 6.37 as the injection currents are scanned from 0 to 100 mA in both mirror sections, the gain section injection current is again held constant at 100 mA. As seen in figure 6.37, 11 modes are accessible with SMSR greater than 30 dB. An output spectrum for a particular set of mirror injection currents giving good single mode operation with a high SMSR is shown in figure 6.38 below.
Figure 6.37. SMSR versus wavelength for both mirror section injection currents scanned from 0 to 100 mA.

Figure 6.38. Typical laser output spectrum of super-mode with a high SMSR. Inset longitudinal modes of the laser cavity.

Closer inspection of the cavity mode spacing reveals that the effective optical length of the laser cavity is significantly shorter than the actual physical laser length. With a central 500 μm section and two mirror sections with lengths of 873 μm and 972 μm
the total laser physical length is 2345 µm in length. However as can be seen in figure 6.39 below the mode spacing is 0.25 nm which from equation (6.18) gives an effective optical length of ~ 1300 µm

![Graph showing output power versus wavelength with mode spacing highlighted](image)

Figure 6.39. Close up of longitudinal mode spacing of the three section slotted laser diode.

with $\Delta \lambda$ the mode spacing equal to 0.25 nm. As the effective optical length is much shorter than the cavity length we deduce that the majority of the mirror reflections are produced by the slots and not by the cleaved facet. To prove this fact we then removed the reflection associated with the cleaved facets by using a focussed ion beam (FIB) to angle the output to 7° which reduces the power reflection from ~ 0.3 to ~ 0.06. Before and after SMSR's versus wavelength are plotted in figure 6.40 and we can see that there is no major deterioration in the laser diode output signal due to removal of the cleaved facets.
Figure 6.40. SMSR versus wavelength both before and after angling both facets a 7°.

Figure 6.41 shows the coupled output spectrum at different injection currents showing high SMSR lasing at 13 distinct super-mode positions over a 35 nm tuning range at a super-mode spacing of ~ 3.2 nm (400 GHz).

This is a major advantage of this laser technology that all the feedback necessary for laser operation is from the slots etched into the waveguide and therefore we are not required to cleave the laser. This means that the laser can be integrated easily with other optical components such as Mach-Zehnder Modulators (MZM), or semiconductor optical amplifiers (SOA). The laser is now demonstrated with an extra SOA section included after the front section which when electrically pumped should amplify the light in the cavity.
As observed in figure 6.41, there is a trade-off between the wavelength tuning range and variations in the output power due to the requirements on the injection current in the output mirror section. To both increase and balance the output power between the different wavelength channels a semiconductor optical amplifier (SOA) is desired. The laser shown here is a six section device, first section is a SOA section ~ 700 µm long. The second section is the front mirror section with 9 deep (down to just above the active region) slots spaced at 97 µm apart with a total length of 873 µm. The third section is the central gain section with no slots and is 500 µm long. The forth section is the back mirror section with 9 deep slots spaced at 86 µm apart with a total length of 774 µm. The fifth section is an extra section to ensure that all the lasers on the bar are the same length to make cleaving easier during fabrication as all lasers were initially fabricated with cleaves which were angled after initial characterisation to determine if the cleave or slots provide the majority of the reflections necessary for lasing. The sixth section is a photodetector section. The first 4 sections are all contacted to individual current sources (CS) and the last two are left un-contacted. The laser is shown below in figure 6.42.
The device was fabricated as above and then a focused ion beam (FIB) was used to electrically isolate the SOA from the front mirror section and the back mirror section from the extra section. Before using the FIB, the resistance between the SOA and front section was measured to be ~ few ohms, while after the resistance was measured to be ~ 1 kΩ which is reasonable in providing electrical isolation from other sections. The FIB ‘slot’ is shown in figure 6.43.

This device was then set up and a two current scan was conducted on it. The SOA section and the gain section was held constant at 100 mA each while the front and back mirror sections were scanned from 250 to 0 mA. A plot of SMSR versus wavelength was plotted and revealed very poor super mode tuning as shown in figure 6.44.
Upon closer inspection of the SOA section it was observed that it will lase with pronounced supermodes. The SOA's output facet is angled at 7° to reduce reflections however there will still be ~ 6 % power reflection from this front facet. The SOA and front mirror section is isolated by the FIB ‘slot’. For the SOA output to show supermodes the front mirror slots must be used as the back SOA reflector. If this is the case then there must be current leakage into the front mirror section from the SOA section as the front mirror is not driven. We devised two schemes to observe this current leakage. The first is to leave the front section as an open section i.e. electrons and holes that leak into the front mirror are free to recombine in the active region, the second scheme is to short out the front mirror therefore any current leaking into the front mirror will go to ground and no recombination will take place in the active region. During both these schemes the voltage is recorded across the front mirror section. A simplified schematic of the setup is shown in figure 6.45 below.
Figure 6.45. Set up schematic, CS – current source, SOA – semiconductor optical amplifier, FM – front mirror, 2 shows the short over the front mirror section.

The spectral output is shown in figure 6.46 below, where the SOA injection current is 100 mA in each plot.

As can clearly be seen there is considerable current leakage into the front mirror section from the SOA section, in 2 above with the front mirror section shorted we see a dramatic decrease in the influence of the slots, however there is still some influence. The voltage recorded across the front mirror section for scheme 1 was 1.4 V and for scheme 2 was 1.5 mV. When the front mirror section is open the SOA output spectrum gives a cavity length of 913 μm by using the cavity mode spacing and when the front mirror is shorted it is 783 μm, the actual physical length is 754 μm. This was repeated for the centre gain section by connecting the SOA and front mirror sections together and biasing them at 200 mA while the back mirror section was biased at 100
mA. The central gain section was first left as an open circuit and then shorted as shown schematically in figure 6.47 below.

![Schematic Diagram](image1)

Figure 6.47. Simplified schematic set up.

Using this set up the isolation slot is the fabricated slot between the front mirror and gain sections which while showing an improvement still a marked difference in output spectra was observed, thus suggesting that the isolation centres between the sections in our laser designs while providing high resistance from contact to contact still allow the flow of charge between the sections and through the active region. The resistance measurements measure the flow of current from one contact to another as shown below in figure 6.48.

![Resistance Measurement](image2)

Figure 6.48. Resistance measurement current path.

However the injected current for lasing will follow a different path as shown below in figure 6.49.

![Injected Current Path](image3)

Figure 6.49 Injected current path through laser.
So even when the resistance is shown to be high to provide electrical isolation, we still see some current leakage into the adjoining sections. Therefore figure 6.44 shows weak super mode hops because the output wavelength is dependent on the SOA injection current as well as that in the mirror sections. This can be improved by reducing the SOA injection current as then the leakage into the front mirror section will be less giving less mode selection by the SOA. This result is shown in figure 6.50 below.

![Figure 6.50. SMSR versus wavelength for different SOA injection currents](image)

As can be seen many more modes can be accessed by reducing the SOA injection current. As all the slots between sections allow some current leakage we need to short out this leaked current to get more regular wavelength and SMSR maps and one way to do this is to have a short section between each section shorted to ground as shown in figure 6.51 below.
This scheme is to etch a shallow slot a few \( \mu \text{m} \) from the last mirror etched slot and to short out this section in between the slots. The slot will have to be shallow as a deep slot will provide large reflections and will therefore destroy the reflection spectra and in the case of most of our laser designs the 400 GHz super mode spacing. The slot will still introduce some loss and the injection efficiency will be reduced slightly however we estimate that this will be low enough to discard. The extra sections introduced between the main sections will have to be short (few \( \mu \text{m} \)) as any longer will introduce strong absorption in this region.

As the SOA section in the present design cannot be used as an SOA section to both increase and to balance the output power between the different wavelength channels the SOA section is then connected to the front mirror section as a continuation of the front mirror section. The injected current can then be increased in this larger front mirror section over the present limit of 200 mA. The injected current in the front and SOA section in the following characterisation is scanned from 0 to 400 mA while the back mirror section injected current is scanned from 0 to 200 mA. The gain section is again held constant at 100 mA. The back sections are left un-biased. The experimental set up is shown schematically in figure 6.52 below.
Figure 6.52. Schematic set up to characterised tunable laser diode.

The coupled output power (figure 6.53), output wavelength (figure 6.54) and SMSR (figure 6.55) maps are shown below. Figure 6.56 shows the super-mode islands more clearly.

Figure 6.53. Coupled output power versus injection currents.
Figure 6.54. Wavelength versus injection currents.

Figure 6.55. SMSR versus injection currents.
From these figures (6.53 to 6.56) clear super mode positions with high SMSR are observed over a discrete discontinuous tuning range of over 40 nm. Plotting the data as SMSR and coupled output power versus wavelength shows the regions of high SMSR and power at particular wavelengths as in figure 6.57 below. This figure shows that ~ 14 distinct super-mode positions are visible. Some of these are very broad (>1 nm) and it is difficult to determine if this is one mode or two. The continuous tunability of these slotted laser diodes will be examined in chapter 7.
The isolation between the sections of all the lasers fabricated was measured and the laser with a high isolation between the sections was chosen to test the SOA section.

The laser chosen has a SOA section consisting of a 645 μm long waveguide section on the output section of the tuneable laser. The SOA output waveguide is curved to at an angle of 6°. This together with an antireflection coating is used to reduce back-reflections into the from the SOA output. The rear section of the laser is terminated by a 746 μm long absorber section and an antireflection coated facet. This section can also be used as an integrated photodetector. Figure 6.58 shows the output characteristics of the device with seven wavelength channels spaced 3.2 nm (400 GHz) apart. The optical output power is significantly increased by the SOA with channel powers ranging from 10 dBm to 14.2 dBm. All seven channels exhibit an SMSR greater than 30 dB with a maximum SMSR of approximately 40 dB. Depending on the application of the wavelength tunable laser only small variations of the output power of different wavelength channels can be tolerated. With the integrated SOA power equalisation of six of the seven wavelength channels is demonstrated. The power flatness achieved was 1 dB. However, this value is not determined by the SOA dynamic range but by the degree of control over the laser wavelength tuning. In this device thermal and electronic crosstalk becomes significant due to the close proximity of laser and SOA with high drive current into the SOA.
Heat and current from the SOA section can dissipate into the front mirror of the laser, changing the local refractive index and in turn the mirror reflectivity spectrum and laser output wavelength. This means that changing the laser output power not only requires a change in the amplifier drive current but also reprogramming of the laser tuning currents. This adds an additional dimension to the laser control problem. The wavelength could be controlled through a look-up table that links wavelength and output power with the required tuning and amplifier currents and which has to be acquired experimentally. Power equalisation can be improved by increasing the amount of points used in the look-up table. Figure 6.59 shows the power current relationship at different SOA injection currents. For this measurement the gain and mirror sections are connected together. The device exhibits an optical output power in excess of 30 mW for an SOA current of 250 mA. The graph shows how increased current injection into the amplifier increases the output power and delays the onset of gain saturation.

Figure 6.58. Seven selected wavelength channels accessible by the laser integrated with an SOA
Conclusion

The tunable lasers shown in this provide > 50 nm tuning with high (> 25 SMSR). The output wavelength shows the designed 3.2 nm super mode spacing which can be controlled by the distance between the slots etched into the laser waveguide. As the lasers described in this chapter are regrowth free, therefore no cleaved facets are required and the laser can then be easily integrated with other photonic components. This is shown above as the laser is monolithically integrated with a semiconductor optical amplifier which is used to boost and balance the output power of the different super modes.
References


Chapter 7 - Tunable Laser Diode - Advanced Characterization

Introduction

In Chapter 6 tunable laser diodes fabricated using etched slots into the ridge and through the upper confinement layer to provide selective reflectivity of particular longitudinal modes of the laser cavity were introduced. The large scale tunability of these diodes were simulated and experimentally determined. 400 GHz super-mode spacing was demonstrated which is useful in implementing wavelength division multiplexing (WDM) which is a standard technique used in optical communications. The international telecommunications union (ITU) had first standardised the channel frequencies of WDM systems on a 100 GHz (0.8 nm) grid in the frequency range of 186 to 196 THz (1530 to 1612 nm – C and L bands). More recently, the ITU has specified 50 GHz in the C and L bands [1]. In order for this laser to have 50 GHz super mode spacing the slot spacing would have to be ~ 850 μm which with nine slots would make the laser ~ 15 mm long with two such mirror section and a gain section. To provide exact ITU grid wavelength the laser needs to be continuously tunable over some wavelength range. This can be realised by both thermal tuning or current injection tuning as will be demonstrated here and a continuous tuning of the laser can access all wavelengths in ~ +/- 100 GHz wavelength range around each super-mode position. Also a four section laser will be characterised which provides finer tunability using the quasi-continuous tuning method as described in chapter 2, as it includes a small section which acts like a phase section in a SG-DBR laser however, it is also an active section in this design. The laser will be further characterised by determining the linewidth over a selected wavelength and the switching speed will also be determined in this chapter.
Continuous tuning of the three section slotted laser diode.

From the wavelength maps in chapter 6, figures 6.54 and 6.55, we see that the tuning of the laser diodes show small changes in the wavelength before the onset of a super-mode hop. These plateaux are areas of continuous tuning which are accessible to the laser. Figure 7.1 below shows an intermixed laser and concentrating on the third super-mode operating at ~ 1495 nm, two different tuning schemes can be seen. In figure 7.2 the blue line represents one current tuning while the green line represents two current tuning.

![Figure 7.1. SMSR versus wavelength for intermixed three section laser diode.](image1)

![Figure 7.2. SMSR versus wavelength for the third super-mode shown in figure 7.1.](image2)
To tune along the blue line one mirror section current is held constant and the other mirror section current is scanned over a particular wavelength. To tune along the green line both mirror section currents are scanned simultaneously. For the continuous tuning to be truly continuous both injection currents need to be changed (increased or decreased) linearly as the wavelength is recorded. To find the maximum SMSR over this wavelength range for linear increasing or linear decreasing mirror section injection currents the injection currents which give the green line in figure 7.2 are found and a linear fit to each is determined which are shown in figure 7.3 below. Increasing these currents will produce a blue shift in the output wavelength (i.e. right to left in figure 7.2)

![Figure 7.3. Mirror injection currents for the super-mode shown in figure 7.2.](image)

For true continuous tuning both injection currents are required to be tuned in a linear fashion and neither jumps in output wavelength or injection currents are tolerated. Therefore the linear fits to the injection currents as shown in figure 7.3 are used to give the maximum SMSR over this wavelength range. We get a final mirror section injection current dependence as shown in figure 7.4 below.
Figure 7.4. Linear injection current for maximum SMSR for third super-mode.

Figure 7.4 shows plots the front and back liner fits found in figure 7.3. Using this injection current configuration the following SMSR and power versus wavelength dependence is obtained as shown in figure 7.5.

Figure 7.5 SMSR versus wavelength for linear increase in both mirror injection currents.
The continuous tunability measured by this technique for the mode shown above is 1.15 nm (~ 140 GHz) with an SMSR of over 33 dB. The output power is also displayed versus the wavelength for this tuning mechanism in figure 7.5. A 3 dBm change is shown over this tuning range which can be balanced using a properly isolated SOA section in front of the output mirror section. The continuous tuning due to linear decreases in the injection currents in each mirror section of the first three super-modes of the laser depicted from figure 6.53 to figure 6.56 in chapter 6 are shown below in figures 7.6, 7.7 and 7.8.

Figure 7.6. Continuous tuning of first mode of laser depicted in figure 6.53 with a linear decrease in both mirror injection currents.

Figure 7.6. Continuous tuning of second mode of laser depicted in figure 6.53 with a linear decrease in both mirror injection currents.
These modes exhibit a continuous tuning of 1.32 nm (~ 165 GHz), 1.65 nm (~ 200 GHz) and 0.83 nm (~ 100 GHz) respectively which allow for accurate setting of the laser to precise optical frequencies. The continuous tuning of these modes by current injection suggests that full carrier clamping does not take place in the mirror sections of this laser. In comparison, an SGDBR laser has a continuous tuning range of <0.4 nm for all discrete modes which is limited by the longitudinal mode spacing, although its quasi-continuous tuning range is much greater [2, 3]. Figure 7.7 shows the evolution of the wavelength and the associated SMSR due to thermal effects associated with a change of heat sink temperature from 5 to 25 °C, here the temperature is varied linearly over this range increasing from left to right. Figure 7.7 also shows the injection current continuous tuning of this mode at different heat sink temperatures to contrast to both tuning regimes. A continuous tuning of over 2 nm while maintaining a SMSR of over 30 dB is measured. The change in wavelength with temperature is in line with the change in the index of InP which is 1.9x10^-4 /K.
While this continuous tuning range is large, it is still much smaller than the 3.2 nm (400 GHz) super-mode spacing and therefore cannot be used to give complete wavelength coverage over the entire wavelength range accessible to the laser diode. If another section is included in the laser design the quasi-continuous tuning range can be increased which will fill in some of the wavelength gaps between the super-modes. The next section deals with a four section slotted laser diode.
**Four section slotted laser diode.**

Including another section between the gain section and one of the mirror sections can improve the quasi-continuous tuning of the laser diode. This is achieved as this section can act like a phase section in an SG-DBR laser. When the wavelength of minimal round trip loss is tuned while the phase section is held constant, the emission wavelength jumps to an adjacent super-mode if this adjacent super-mode experiences a lower loss, this is the called discontinuous tuning (as describe in chapter 2). By changing the phase section injection current the whole tuning map can be shifted by an amount relative to the injection current in the phase section. Figure 7.8 below shows the four section laser schematic with the extra phase section included between the gain and back mirror sections.

![Figure 7.8. Four section slotted laser schematic.](image)

Figure 7.9 shows the SMSR versus wavelength for this laser as the injection currents in the mirror sections are scanned from 0 to 100 mA and the phase section is held at 5 mA.
Figure 7.9. SMSR versus wavelength for a set phase injection current, while both mirror sections are scanned from 0 to 100 mA.

Five super-mode positions are seen in this figure at ~ 3.2 nm super-mode spacing. Concentrating on super-mode at ~ 1505 nm we look at its continuous tuning in figure 7.10 for three different phase currents.

Figure 7.10. Continuous tuning for four section laser at different phase section injection currents.
This laser shows a redshift in wavelength as the injection current is increased. This may be due to thermal effects. The thermal redshift effect can be much stronger than the carrier blueshift effect therefore the blueshift seen in previous graphs (eg figure 7.6) has to overcome the thermal redshift if the laser is not properly thermally controlled. As the injection of carriers into the laser causes an increase in temperature this may explain the redshift seen in figure 7.10. Increasing the phase section injection current produces a red shift, possibly due to poor thermal control, in the entire output wavelength position. In this case the wavelength coverage is increased from 0.35 nm to 0.65 nm by a 20 mA change in the phase section injection current. In order to get full wavelength coverage the four section laser has to be optimized so that the supermode spacing can be entirely filled by changing the phase section injection current.
Three section slotted laser diode linewidth measurements.

In this section the laser linewidth is introduced and determined. A more rigorous linewidth description can be found in [4-6]. The linewidth of a laser diode is an important parameter in optical communications as a broad linewidth will reduce the distance over which the laser pulse can be transmitted due to dispersion in the optical fibre. However even single mode lasers have a finite linewidth caused by spontaneous emission into the lasing mode as the spontaneous emitted photons will have a random phase with respect to the coherent emission generated by stimulated emission. The number of photons in the laser cavity and the optical power depends on the laser structure therefore the linewidth depends on the laser structure. The number of photons in a laser cavity is determined by (7.1) below.

\[ S' = \frac{\bar{S}V_a}{\Gamma} \]  

(7.1)

where \( \bar{S} \) is the average photon density, \( V_a \) is the active region volume and \( \Gamma \) is the confinement factor. From [4] the change in phase \( \Delta \phi_i \) due to the addition of a photon with random phase is given by (7.2).

\[ \Delta \phi_i = \frac{1}{\sqrt{S'}} \sin(\theta_i) \]  

(7.2)

where \( \theta_i \) is taken from figure 7.11 below.

Figure 7.11. Phasor representation of the field in a laser, showing the result of one spontaneously emitted photon. The field amplitude \( \beta = 1^{10}\exp(i\phi) \) increased by \( \Delta \beta \), having amplitude of unity and phase \( \phi + \theta_i \).
Therefore over time \( t \) the statistical phase change is given by (7.3)

\[
\Delta \phi(t) = \sum_{j=1}^{n} \frac{R_{sp} V_a / \Gamma}{\sqrt{S^t \sin(\theta_i)}} \quad (7.3)
\]

where \( R_{sp} V_a / \Gamma \) is the spontaneous emission rate. By equating the variance per time of \( \phi(t) \) to a change in angular frequency we can find an expression for the laser linewidth (\( \Delta \nu \)) as

\[
\Delta \nu = \frac{\Delta \omega}{2\pi} = \frac{R_{sp} V_a / \Gamma}{4\pi S^t} \quad (7.4)
\]

where the variance is given by

\[
\text{var} \left[ \frac{\Delta \phi(t)}{t} \right] = \left\langle \left[ \phi(t) - \phi(0) \right]^2 \right\rangle = \frac{R_{sp} V_a / \Gamma}{2S^t} = \Delta \omega \quad (7.5)
\]

The distribution of \( \Delta \phi(t) \) is Gaussian which leads to a Lorentzian lineshape. As the spontaneous emission \( (R_{sp}) \) can be described as (7.6) from Einstein’s relations

\[
R_{sp} = \frac{\Gamma v_g g_{eff} n_{sp}}{V_a} \quad (7.6)
\]

where \( v_g \) is the group velocity, \( g_{eff} \) is the modal gain and \( n_{sp} \) is the spontaneous emission coefficient \( (n_{sp} \sim 2-3) \) and the power out of each facet is

\[
P = \frac{v_g \alpha_m S V_a h \nu}{2\Gamma} \quad (7.7)
\]

where \( P \) is the power out of each facet assuming that both facets are equal, the linewidth can be written as

\[
\Delta \nu = \frac{h \nu v_g^2 (\alpha_i + \alpha_m) \alpha_m n_{sp}}{8\pi P} \quad (7.8)
\]

where \( \alpha_m \) is the mirror loss, \( \alpha_i \) is the internal loss and \( h \nu \) is the photon energy. This is the Schawlow-Townes expression for the laser linewidth. As described in chapter 4 for a semiconductor laser there is an extra enhancement to the linewidth called the linewidth enhancement factor (\( \alpha \)) due to phase noise which is created when
spontaneous emission from the laser cavity gain media changes the laser frequency. This occurs when a spontaneous emission event changes the photon density which changes the carrier density as the carrier and photon densities are related through the carrier and photon density equations. This enhancement of the linewidth is given in [5] and the linewidth can be written as

$$\Delta \nu = \frac{\hbar \nu^2 (\alpha_i + \alpha_m) \sigma_m n_p}{8\pi P} \left(1 + \alpha^2\right) \quad (7.9)$$

which is termed the Schawlow-Townes-Henry linewidth.

As the linewidth, even with these broadening mechanisms is still of the order of a few MHz normal measurement equipment (optical spectrum analyser (OSA) etc) cannot determine this as an OSA has a resolution down to ~ 11\(^{-11}\) m (0.01 nm) (~ 1.25 GHz) while the laser linewidth is of the order of 1\(^{-14}\) m (10 MHz). In order to determine the laser linewidth another method which does not rely on an OSA to measure the spectrum is required. The measurement scheme used to determine the tunable laser diode (TLD) linewidth is the delayed self-homodyne (DS-H) method and provides very high resolution (~10 kHz – 1GHz resolution). The basics of this method are presented here. Firstly the laser has to be operating in a single mode regime, that is that the SMSR has to be high (>25 dB). Interference between two optical fields are used in this method where the two optical fields used are the original beam and a time delayed portion of itself. For this method to work both beams must have spatial overlap and polarization alignment. The first of these is obtained by sending both optical waves down the same single mode fibre which ensures good spatial overlap. The second is obtained by including a polarization controller (PA) in the setup to create a polarization overlap between the optical waves.

Delayed Self-homodyne: interference between a field and a delayed portion of itself

Here we analyse the delayed self-homodyne (DS-H) method to determine the optical linewidth of a semiconductor laser, a more detailed analysis can be found in [7]. Consider an optical field and its delayed self, incident on a photodetector after being spatially combined in an single mode optical fibre. The optical fields take the form

$$E_1(t) = \sqrt{P_1(t)} \exp[i(2\pi v_1 + \varphi_1(t))] \quad (7.10)$$
and

\[ E_2(t) = \sqrt{P_2(t)} \exp[i(2\pi v_2 + \varphi_2(t))] \]  \hspace{1cm} (7.11)

where the delayed field is denoted with a subscript 2. The fields amplitude squared are optical powers i.e.

\[ P_i(t) = |E_i(t)|^2 \]  \hspace{1cm} (7.12)

where \( \varphi_i \) is the optical phase and \( v_i \) is the frequency of the \( i^{th} \) field. As the photodetector detects the power and not the optical field itself the detected power is

\[ i(t) = \Re|E_i(t)|^2 = \Re|E_1(t) + E_2(t)|^2 \]  \hspace{1cm} (7.13)

where \( \Re \) is the detector responsivity

\[ \Re = \frac{\eta_d q}{h\nu} \]  \hspace{1cm} (7.14)

where \( \eta_d \) is the detector quantum efficiency and \( q \) and \( h\nu \) are the usual electronic charge and photon energy which for a wavelength of 1550 nm \( q/h\nu \) has a value of 1.24 eV. Therefore the final power detected at the photodetector is

\[ i(t) = \Re[P_1(t) + P_2(t) + 2\sqrt{P_1 P_2} \cos(2\pi v_0 \tau_0 + \Delta \varphi(t, \tau_0))] \]  \hspace{1cm} (7.15)

where \( P_1 \) and \( P_2 \) are the powers measured by the photodetector from the optical field and its delayed self, \( 2\pi v_0 \tau_0 \) is the average phase-setting of the interferometer used where the delay between both optical fields is \( \tau_0 \), and \( \Delta \varphi(t, \tau) \) is the time varying phase difference caused by any phase or frequency modulation and the interferometric delay \( \tau_0 \).

The experimental set-up used to measure the linewidth of a TLD is described in figure 7.12 below.
The free space optical isolator gives 60 dB isolation between forward and backward propagating light. 1 % is coupled to the optical spectrum analyser (OSA) to determine the wavelength of the super-mode under inspection. The 99 % portion of the light is split again in the interferometer and one half is sent through 5.2 km of optical fibre that produces a delay of 25 μs. The delay must be more than the coherence time of the laser meaning the two beams will combine as if they originated from two different sources giving incoherent mixing. The other path goes through a polarization controller to ensure the polarization is closely matched to maximise the interference between the two signals. This process is equivalent to mixing two lasers with the same linewidth and central frequency. As the laser has a Lorentzian lineshape the displayed electrical spectrum on the RF analyser will have a similar shape as the shape is preserved through the autocorrelation operation. As this method centres the mixing spectrum around 0 Hz only half of the symmetrical lineshape is visible. Figure 7.13 below shows the electrical spectrum for the TLD at an operating wavelength of 1557.4 nm. The electrical detector has a frequency limit which can be seen as a spike at around 0 Hz and extends to around 2 MHz, therefore the data below this electrical roll off is discarded which is shown in the inset. In long delay measurements such as this, the lineshape at low values of frequency tend to be Gaussian due to the presence of 1/f shot noise so even more can be discarded giving an improvement to the linewidth measurement.
The spectral linewidth versus operating wavelength is determined by the above method where the operating wavelength is tuned by changing the injection current in both mirror sections of the laser. The recorded data is shown in figure 7.14 below.

Figure 7.13. RF photocurrent spectrum for TLD at 1557.4 nm, with inset showing the used portion of the data with a linewidth of 15.2 MHz.

Figure 7.14. RF photocurrent spectra for different super-mode positions.
The linewidth calculated from figure 7.14 for different wavelengths is shown in figure 7.15 below. A clear dependence of the spectral linewidth on wavelength is observed which is seen in other tunable laser diodes as seen in [4]. The linewidth enhancement factor was shown to increase to longer wavelengths from chapter 4, this is reflected in the linewidth versus wavelength figure below.

One limitation with this method is due to the currents used to control the injection into the laser sections. As with any current source some noise fluctuations will be present and the ILX current supplies used for this experiment has an 8 pA noise level. As the laser is biased with three independent current sources it was not possible to replace them with low noise current sources, therefore the values determined here may be significantly larger than the intrinsic value of the laser. Typical values for semiconductor laser linewidths are between 10 to 100 MHz, but linewidths as low as 400 kHz have been reported in [8] for certain types of grating structure tunable lasers.
Three section slotted laser diode switching measurements.

As stated in the beginning of chapter 6 the laser design presented in this thesis may have many applications. One application is as sparing applications in dense wavelength division multiplexing systems. For this application the tunable laser is just used to reduce the cost of having a backup for each wavelength, therefore no switching is needed and therefore the switching speed is irrelevant. For trace gas detection a high wavelength stability and narrow-linewidth are required though the switching speed is not critical although large wavelength continuous tuning is required. Wavelength-agile networks are also simplified with tunable lasers where reconfigurable optical add-drop multiplexers (ROADMs) and wavelength based routing are used. The use of widely tunable lasers helps maximize existing network resources. The ability to dynamically provision bandwidth provides the ability to optimize the network configuration to meet demand. Widely tunable lasers move traffic from overcrowded channels to unused channels and are becoming essential for the network architecture. Remote provisioning of optical paths using tunable lasers can be performed infrequently with a particular network configuration remaining unchanged for a period of months or years. Such "static" provisioning has effectively no switching speed requirement. Future DWDM networks will make more use of wavelength converters to increase network flexibility. Wavelength converters, such as, optical-electronic-optical (OEO) converters have the ability to detect a high data rate signal on any input wavelength channel and to convert to any output wavelength channel, using tunable lasers. Future uses for tunable lasers will also include packet based selection of the wavelength on which the packet is to be transmitted. The tunable laser switching speed for these applications will be of the order of microseconds or higher.

Therefore from the above analysis a fast switching speed (of the order of ns) is not required in the near future. Here we analyse the three section tunable laser diode (TLD) as describe in the previous sections in terms of their switching speed. The method used is an optical heterodyne method which is similar to the optical homodyne linewidth method described above, however an external cavity laser is used instead of an interferometric delay, background can be found on it in [7,9,10]. The experimental set-up is shown in figure 7.15.
Three section tunable laser

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**Figure 7.15.** Experimental set-up to determine switching speed of TLD. OSA - Optical spectrum analyser. COM - optical combiner, PG - pulse generator, ECL - external cavity tunable laser, PA - polarization adjuster, FPD - fast photodetector, RFSA - radio frequency spectrum analyser.

The gain section and the front section of the three section laser is held at a constant value (~ 100 mA in each section). The pulse generator sends a square wave pulse to the back section and switches it between two injection currents which are known to produce high SMSR lasing at two different wavelengths. The pulse generator has frequency set to 25 MHz. The two wavelengths are channel 1 = 1553.7 nm and channel 2 = 1557.3 nm. The time averaged output spectrum is shown in figure 7.16 below which is recorded with the OSA.

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**Figure 7.16.** Time averaged spectrum recorded on the OSA showing both super-modes.
Applying the square wave pulse changes the injection current which changes the output lasing wavelength faster than the OSA can record so a time averaged spectrum has to be found to give the results obtained in figure 7.16. The external cavity tunable laser (ECL) is swept across the wavelength range from 1553 to 1558 nm. The output power versus time and wavelength is recorded using the method described in figure 7.15. The recorded power versus wavelength at different times are shown below in figure 7.17 and figure 7.18.

From figure 7.17 and figure 7.18 two distinct super-modes can be seen to lase depending on the output from the pulse generator. The 25 MHz gives a time of 40 ns of lasing on each channel between switching. By looking at how both wavelength channels (i.e. 1553.7nm and 1557.3nm) evolve with time the switching time can be determined. Figure 7.19 below shows how the output wavelength changes as the laser back section is switched. The switching time is then calculated from this and is shown in figure 7.20 which gives the turn on and turn off time for both channels.
The switching time is usually defined as the time taken for a 3 dB change (i.e. 3 dB lower power than maximum). In order to find the switching time of the laser a closer inspection of figure 7.19 is needed. The 3 dB power change between channel 1 and 2 is 0.93 ns and the 3 dB change between channel 2 and 1 is 0.43 ns.
Figure 7.20. a – channel 2 to channel 1, b – channel 1 to channel 2, where the solid line represents the 3 dB decrease in output power from the channel that is switched off.

However if a channel switches on before the other channel switches off then a negative switching time can be deduced from this 3 dB definition. A better estimation of a laser switching performance is how long a super-mode takes to decrease in SMSR by 30 dB (while switching off), and the other super-mode to increase its SMSR by 30 dB. Figure 7.21 shows this for channel 1 and channel 2.
Figure 7.21. Channel 1 switch on time (1) and switch off time (2), Channel 2 switch on time (3) and switch off time (4).

Figure 7.21 shows time taken for both channels to switch on (1 and 3) from 30 dB below the maximum output value and to switch off (2 and 4) to 30 dB below the maximum output power. The switch on time for channel 1 is ~0.5 ns and for channel 2 is ~1 ns. The switch-off time for channel 1 is ~2.5 ns and for channel 2 is 2.7 ns. As the switch-off time is longest this mostly dictates the switching time. Switching these lasers may induce other super-modes to lase for a very short time therefore the laser needs to be blanked while switching is ongoing if the laser is to be switched while in an optical network.

Conclusion
Up to 1.65 nm of continuous tuning is shown in this chapter while thermal tuning of ~2 nm is also shown. To increase the overall tunability of this laser design another section is included and the quasi-continuous tuning scheme is employed to achieve additional wavelength coverage at the expense of device simplicity. To fully characterise the laser the linewidth and switching speed of the laser is measured. The linewidth is determined to be 15.2 MHz at a wavelength of 1557.4 nm and increases as the wavelength is tuned to the red end of the spectrum. The switching speed is shown to be dominated by the turn off speed and is measured to be ~3 ns.
References


Chapter 8 - Conclusion

Much work has been done on tunable laser diodes for optical communications and the work presented here suggests an alternative approach to produce good quality tunable semiconductor lasers. In Chapter 4 some new techniques for characterisation of laser diodes were outlined. The linewidth enhancement (alpha) factor is important for tunable laser diodes as a larger linewidth enhancement can give a larger linewidth which will cover more cavity/longitudinal modes providing easier continuous tunability of the super mode position. The method described to measure this alpha factor is a simple technique based on a Fourier series expansion which includes a correction for the finite bandwidth of the optical spectrum analyser (OSA). This was shown to provide a better level of accuracy than previous methods. Also in chapter 4 the waveguide loss was measured by two new techniques, the merits of which are that they can be used when only one facet is accessible. One method uses an external cavity tunable laser and a photodiode to record the reflection spectrum while the other uses a broadband source and an OSA to measure the reflection spectrum where again a correction factor is used to account for the resolution of the OSA. The spontaneous emission and quasi-Fermi level separation for a laser diode was also measured and the internal and external quantum efficiency was determined for a laser diode. These results are important for the characterisation of the tunable laser in later chapters.

In chapter 5 single slot lasers where the slot is etched into the ridge waveguide of a simple Fabry–Pérot laser were introduced. The slot modulates the output spectrum by suppressing some cavity modes of the laser. This laser design is introduced from the scattering matrix method and the experimental results are given for this laser design. The reflection and transmission of the slot is determined from the amplified spontaneous emission (ASE) spectrum by using the Fourier transformed spectra and values estimated from a theoretical analysis.

In chapter 6 tunable laser diodes based on multiple slots etched into the ridge of various laser designs were introduced. The best tunable laser fabricated is shown to be a three-section laser with nine slots etched into each mirrors section with a gain section in the centre. The laser was shown to operate with good single mode operation and access to supermodes at 3.2 nm spacing (400 GHz).
In chapter 7 some more tunable laser characterisation were introduced by concentrating on the three-section laser and determining the continuous tuning to be over 1 nm by current injection and over 2 nm by thermal tuning. A four-section laser is described which increases the continuous tunability of the laser in a quasi-continuous fashion. The laser linewidth is also determined to be ~ 15 MHz and increases as the laser is tuned to the red end of the spectrum. The switching speed of the laser is also determined and calculated to be ~ few ns.

These experimental results suggest that this type of tunable laser can be used in optical communication systems. The most obvious advantage of this laser is its ability to be monolithically integrated with other optical components as there is no need for a cleaved facet for laser operation. This has been shown in chapter 6 where the laser is integrated with a semiconductor optical amplifier to increase and balance the output from each super-mode. These lasers could be used as back up for single frequency lasers in dense wavelength division multiplexing (dense WDM) optical communication systems but have great promise in replacing such single mode lasers completely. The lasers shown here have 3.2 nm super-mode spacing, however this can be decreased by increasing the distance between the slots in the mirror section. Other applications for these lasers are as sources for spectroscopic gas sensing in environmental emission monitoring.

Future applications for this laser is within the development of photonic integrated chips similar to the silicon electronics industry where multiple applications are integrated on a single chip to further reduce the cost of photonic components. This laser is now being integrated with two Mach-Zehnder interferometers (MZI) which is shown schematically in figure 8.1 below.

![Figure 8.1. Schematic of a tunable laser and two MZI's on chip.](image-url)
The first MZI modulates the continuous wave laser output producing a stream of pulses while the second modulates the pulses in accordance with the modulation format used.

Other future work if the laser is to be commercially manufactured for use in optical communications is to decrease the super-mode spacing. This can be achieved by increasing the slot spacing however this also increased the laser length and a trade off is needed between the laser length and the super-mode spacing. The lasers described in this thesis are proof of concept devices and there needs to be a full characterisation of many devices to determine the optimal device parameters.