Diode Lasers with Optical-Feedback, Optical-Injection, and Phase-Conjugate Feedback

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Summary

Semiconductor diode lasers are currently used in numerous applications. Optical feedback and optical injection are known to induce a diverse range of effects, which can be beneficial or detrimental to the operating characteristics of such devices.

This thesis presents a primarily experimental investigation of the effects of optical feedback, optical injection, and phase conjugate feedback, on a range of the operating characteristics of a solitary diode laser. Specifically, the stability, the output power, and the frequency modulation characteristics are examined and compared for several different diode lasers.

The main results of this research are summarised as follows:

• The injection of charge carriers into a diode laser gain region (via optical feedback) can reduce the output power (relative to that of the free-running device) for certain operating parameters. In some lasers this is accompanied by an increase in spatial and spectral hole-burning.

• Regimes of instability in the parameter space of optical feedback level, feedback phase, external cavity length, and injection current are strongly influenced by the internal parameters of the solitary diode laser. Two different diode lasers display significantly different behaviours.

• Strong optical injection can suppress the transition into dynamic instability caused by optical feedback. This result may be applied to generate a diode laser device that is insensitive or less sensitive to unwanted optical feedback.

• Phase conjugate feedback in either a broad-area or narrow-waveguide diode laser incites dynamic instabilities that are different from those induced by plane mirror feedback.

• Optical injection suppresses the transition into dynamic instabilities in direct frequency modulated external cavity diode lasers. This indicates the possibility of generating wide bandwidth FM output from diode laser integrated devices.

• The coupling efficiency between the external feedback field and the diode laser gain region for feedback from a plane mirror is three times the coupling efficiency of an injected source and half that from a phase conjugate mirror.
Declaration

This thesis is the sole work of the author. Information arising from other sources and collaborations is indicated in the text or referenced in the usual manner. The research presented in this thesis has not been submitted for a higher degree to any other university or institution.

____________________

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Chapter One: Introduction

1.1. Semiconductors diode lasers

Since the first demonstration of the semiconductor laser (or diode laser) in 1962 [1-4], it has found application in an increasing number of areas. These applications include sources, amplifiers, and multiplexers for optical communication systems [5-7], pump sources for solid state lasers [8,9], sources and reference beams for spectroscopy [10,11], and optical data storage and retrieval [12,13]. Diode lasers are also found in a number of common instruments, such as laser scanners, pointers, barcode readers, and printers.

The widespread use of semiconductor lasers has arisen due to several of their advantageous attributes. They are generally small in size, reasonably efficient, maintenance free, and relatively inexpensive. They require only low power current sources, can be frequency modulated by a direct modulation of injection current, and have been demonstrated to operate at wavelengths from the near ultraviolet [14] to the far infrared [15].

Several factors, however, have limited the applicability of diode lasers. Firstly, free-running narrow-waveguide diode lasers typically operate with a linewidth of ~10-50 MHz, and a side mode suppression > -20 dB. This is far from the ideal narrow linewidth (sub kHz) single-mode emission required in many systems. Secondly, the maximum output power achievable from a narrow-waveguide device (currently < 1W cw [16]) is much lower than that available from other types of laser. Higher power has been demonstrated in broad-area diode lasers and coherent laser diode arrays (currently up to 10 W [17] and 200 W cw [18] respectively), but this is generally accompanied by multi-longitudinal and high-order transverse mode emission. Thirdly, diode lasers typically have poor output beam profiles, particularly when compared to the near diffraction limited output available in other laser devices. The output is highly divergent and elliptical, and thus requires additional collimating and circularising optics for free-space transmission or efficient optic fibre coupling.

Theoretical modelling of the behaviours of semiconductor diode lasers has been an intrinsic and necessary component in the development and application of these devices. A semiclassical treatment generates a generalised form of the Lorentz-Haken equations [19],
which are derived from a macroscopic model of the semiconductor Maxwell-Bloch equations [20]. Adiabatic elimination of the material polarisation then allows the system to be described by two first-order ordinary differential equations, which are known as the semiconductor rate equations [21]. These equations describe the temporal evolution of the electric field and carrier density inside the laser cavity, and are found to adequately predict many aspects of diode laser behaviour, including the output dynamics, frequency profile, and intensity versus current characteristics [22]. These equations are based on a travelling wave description of the electromagnetic fields inside the laser cavity. Current efforts to extend the capabilities of the models rely on developing more accurate descriptions of the gain (including nonlinearities and applicable to quantum well lasers), developing a quantum mechanical description of the laser fields for micro-cavity devices [23], and providing better quantitative agreement with experimental observations by more accurately describing internal laser parameters.

Diode lasers are very sensitive to optical feedback and optical injection [24,25]; this represents the focus of the current research. Injection and feedback phenomena have been studied both as a way of improving the output characteristics of diode lasers and from the pure research perspective. The next section describes the historical background (including the motivations and significant results) of research into diode lasers with optical feedback, optical injection, and phase conjugate feedback.

1.2. Background

1.2.1. Diode lasers with optical feedback

Optical feedback is introduced into a diode laser by returning some portion of the optical output back into the device. This is shown schematically in figure 1.1. The introduction of such feedback has been found to have dramatic and varied effects on the operating characteristics of the solitary diode laser. Feedback can be disadvantageous, as it may cause unwanted instabilities in the laser output, or advantageous, as under certain conditions it can improve various features of the solitary laser, such as increasing the side mode suppression and narrowing the linewidth [24-26].

Research into the effects of optical feedback on the operating characteristics of semiconductor diode lasers was instigated by the publication of Lang and Kobayashi in 1980 [27]. This paper reported the observation of multistable behaviour and hysteresis in the output of a laser diode subject to feedback. Other early research primarily considered the effects of
the feedback on the diode laser noise [28-31] and linewidth [32-36]. Studies on the optical feedback induced deterministic dynamics discovered self-pulsing and chaotic output in diode lasers with feedback [37-39], and recognised that the relaxation oscillation of the solitary diode laser plays a primary role in the induction of these instabilities [40-42]. The region of chaotic instability was termed coherence collapse in 1985 [43]. In 1986, five distinct regimes of operation, which depend on the feedback level, were identified by Tkach and Chraplyvy [44]. These regimes (discussed in section 2.1.1) range from very weak feedback (regime I) to very strong feedback (regime V) [45]. A specific form of instability known as Low Frequency Fluctuation (LFF) was identified in 1988 [46], and has since been examined in detail [47-50].

![Figure 1.1. Schematic showing diode laser subject to optical feedback.](image)

Over the last twenty years hundreds of papers have been published, in both pure and applied areas, on the subject of diode lasers with optical feedback. The large number of publications demonstrates the complex nature and importance of this field. Despite such extensive research there are still many aspects of the behaviour of diode lasers with feedback that are not very well understood. Three primary areas of research (applications, systems engineering, and nonlinear dynamics) are discussed below.

Diode lasers operated with feedback have found applications in a number of areas due to the improvement that the feedback can lead to in many of the operating characteristics of the solitary diode laser. Optical feedback of appropriate level has been found to increase the side mode suppression, narrow the linewidth, and provide enhanced tunability and frequency stability; relative to that of the solitary diode laser [34,51-56]. A source for coherent optical communication systems (particularly for heterodyne detection and wavelength division multiplexing) and spectroscopic applications is required to be single frequency, narrow linewidth, and continuously tunable over a wide range of wavelengths [57-59]. There are many spectroscopic techniques for which diode lasers with feedback are ideal sources [11,60].
Chaotic output may be used to provide secure optical communications [61,62]. For the laser induced cooling and trapping of atoms and the manipulation of atomic beams narrow-linewidth low-power stable tunable sources are required [63]. For these reasons, diode laser with feedback systems are readily available commercially and are used extensively in many areas of research, communications, and industry.

For the design or engineering of any optical system, the effects of optical feedback must be considered. In any practical system that uses a diode laser as a source, there will always be unwanted or spurious reflections. These reflections occur, for instance, from fibre couplers, joiners, collimating lenses, detectors, and any other external optic surface. It is important to fully understand the effects and magnitudes of the feedback (from these reflections) in order that the system components can be designed to take advantage of (or avoid) the feedback that may cause instabilities or a shift from normal operating parameters. Stability criteria, in terms of the levels of feedback that are acceptable (to maintain stable operation) for a range of the system parameters with a given diode in a given system, must be determined [39,64-68].

A large number of theoretical papers and some experimental papers have reported on numerous aspects of the nonlinear dynamics that arise in semiconductor lasers with the presence of feedback. The motivations behind these investigations are that diode lasers with feedback are an example of an interesting optical nonlinear system that displays dynamic instabilities [69-74] and chaotic behaviour [40,41,75-77] for certain levels of feedback. Attributes of the chaotic state, including its noise have been analysed [43,78-81]. The system is modelled mathematically by a set of rate equations known as the Lang-Kobayashi rate equations [27,82,83]. Theses are modified forms of the semiconductor rate equations that describe the temporal evolution of the photon number, the carrier density, and the phase inside the laser active layer, dependent on the feedback level (for weak feedback) and external cavity length.

1.2.2. Diode lasers with optical injection

The process of optical injection is illustrated in figure 1.2, below. A single-frequency signal from a master source, generally a tunable laser, is injected into the active region of the slave laser diode. The master laser is optically isolated from the slave laser (typically by a polarisation dependent optical isolator). Similar to optical feedback, such optical injection has a variety of effects on the operating characteristics of the slave laser. It can: induce various
dynamic instabilities and chaotic behaviour, lock the two lasers together in phase and frequency (injection locking), excite the relaxation oscillation frequency of the slave laser, or produce phase conjugation through four-wave-mixing [84-86].

![Figure 1.2. Schematic of diode laser with optical injection from another laser source.](image)

The theory of injection locking of electrical oscillators, ie the frequency locking of an electric oscillator to an injected signal, was described by Alder in 1946 [87]. This theory was extended to laser injection locking [88], and semiconductor laser injection locking (by analogy with the van der Pol [89] equations) in 1974 [90]. Laser frequency locking was first demonstrated in 1966 with a He-Ne laser [91]. The injection locking of a semiconductor laser (by a gas laser) was reported in 1980 [92], and the experimental coupling of two semiconductor lasers, ie the injection locking of one by the other, was reported in 1981 [93]. The influence of the injected signal frequency and power, and the linewidth enhancement factor of the slave laser has since been analysed [94-97].

Operating semiconductor lasers in an injection locked state has been found to have many benefits. These include linewidth reduction [98], reduction of mode partition noise, single-mode stability [99], noise reduction [100], synchronisation, frequency stabilisation [85,101-103], and modulation suppression [104-106]. Many studies have concentrated on applications that utilise these advantages. These include sources for coherent communication systems, repeaters in long range high-speed digital fibre transmission, and phase modulation systems.

The system behaviour when the diode laser does not lock to the external injected source has also been considered [107-109]. Various dynamic instabilities, including optical chaos, developed through period doubling and intermittency bifurcations have been observed.
and predicted to occur in semiconductor lasers with optical injection. Detailed analysis of such chaotic, periodic, and semi-periodic behaviour is typically mapped as a function of injected power and frequency detuning [84,110].

The generation of a phase conjugate signal through the process of cascade four-wave-mixing by injecting a strong optical signal outside the locking range was reported in 1987 by Nietzke et al [86] and has been extensively examined since [111-114]. Such generation of a phase conjugate signal has also been demonstrated in Semiconductor Optical Amplifiers (SOA) [115], which leads to a particular application. If a SOA is used at the midway point of fibre optic communications network, the phase conjugate signal generated in the SOA is the spectral inverse of the input signal and thus after transmission through an equal distance of fibre, any dispersion introduced in the transmission through the first length is corrected for [116-118].

1.2.3. Diode lasers with phase conjugate feedback

The effects of phase conjugate feedback (PCF) on the operating characteristics of diode lasers are similar in many aspects to those induced by conventional optical feedback (COF). The subject has attracted considerable attention both theoretically and experimentally. Theoretical analysis is motivated by the fact that a semiconductor laser with phase conjugate feedback is an example of a nonlinear system which displays significantly modified nonlinear dynamics from the case of conventional optical feedback. In terms of applications, PCF can be used to provide many of the advantageous aspects of COF with the addition that due to the conjugate process spatial output profiles and coupling are enhanced. A PCF set-up is shown schematically in figure 1.3.

![Figure 1.3. Schematic of diode laser subject to phase conjugate feedback.](image-url)
Phase conjugate feedback is derived from a phase conjugate mirror (PCM), which is a device that has the property of retroreflecting, or phase conjugating, a signal wave that is incident on its surface. An incident electromagnetic wave, \( E \), of frequency \( \omega \), propagating in the forward \( z \) direction may be written

\[
E(x, y, z, t) = A(x, y, z, t)\cos(\omega t - kz - \phi(x, y, z)).
\] (1.1)

The phase conjugate of this wave is described by

\[
E_c(x, y, z, t) = A(x, y, z, t)\cos(\omega t + kz + \phi(x, y, z)),
\] (1.2)

which represents the same wave equation but the longitudinal component of the wave vector, \( k \), and the transverse phase component, \( \phi \), have opposite signs. Thus the phase conjugate wave has the same phase but propagates in the negative \( z \) direction.

This wavefront reversing property of a phase conjugate mirror, compared to the wavefront reflecting property of a conventional mirror, is illustrated in figure 1.4, below. If an ordinary mirror is illuminated by a diverging beam from a monochromatic point source, the mirror simply redirects the diverging beam, changing only the longitudinal component of the wave vector. If, however, a diverging beam from a monochromatic point source illuminates a phase conjugate mirror, the phase conjugate mirror reflects the diverging beam as a converging beam that retracts its original phase path. This occurs regardless of any intervening or distorting medium that is placed between the source and the mirror [119].

![Figure 1.4. Reflective properties of a conventional mirror compared to a phase conjugate mirror when illuminated with a monochromatic beam from a diverging point source.](image)

The first experimental report of a diode laser with feedback from a phase conjugate mirror was by Cronin-Golomb et al in 1985 [120]. Threshold current and slope efficiency reduction, mode-locking, and an induced dynamic instability were observed. Since then, many authors have reported on the experimental effects of single-mode diode lasers with PCF.
These include linewidth narrowing [121-124], self-induced frequency scanning [125,126], enhanced frequency stability [127-129], mode-locking [130-132], and modified longitudinal mode structure [120,123,133-136]. Potential applications include communication systems and spectroscopy due to the potential for improved linewidth reduction compared to COF systems.

Theoretical analysis of the dynamic effects of PCF has also attracted attention. The modified rate equations for optical feedback were first solved for a self-pumped phase conjugator by Agrawal and Klaus in 1991 [137] under the assumption that the phase conjugate mirror responded instantaneously. The laser was found to exhibit various routes to chaos depending on the strength of the phase conjugate reflectivity. Various aspects of the dynamics induced by PCF have been reported [138-140], and compared with dynamics induced by COF [141-143]. More recently, rate equations for PCF have been solved for finite penetration depth and response time phase conjugating mirrors [144-145]. Theoretical descriptions of the effects of PCF on the noise characteristics [146-148] and far-field radiation patterns [149] of diode lasers have also been published.

An area of more practical application of diode lasers with phase conjugate feedback is for broad-area diodes and laser diode arrays. Single longitudinal mode operation, and improvements in the output spatial mode of a high-power broad-area laser diode with PCF has been demonstrated [150-152]. Similarly, laser diode arrays with PCF have been reported to have improved transverse mode profiles (particularly in the far field), higher coupling efficiencies between the LDA and the output optics, and many effects noted for narrow-waveguide diode lasers with PCF, such as linewidth narrowing, frequency stability, and mode-locking [126,153-155].

Enhanced coupling of various laser types using phase conjugate mirrors [156,157] has been extended to diode lasers. Typically, double PCMs are used (in a master/slave or mutual feedback arrangement) to lock two or more solitary laser diodes [158-161], a solitary laser diode with an LDA [162], or two or more LDAs [163]. As each conjugate wave exactly matches the respective laser cavity, locking efficiency is significantly increased, and the devices are automatically aligning [164,165].
1.3. Motivations

There are a number of motivations for the current research into the behaviours of diode lasers with optical feedback and injection. Although the current project is not primarily application based, there are many applications that will benefit from the results of this work in terms of the greater understanding it delivers to the topic. The primary motivation is to provide a comparative experimental study on the effects of optical feedback, optical injection, and phase conjugate feedback on various aspects of diode laser operation.

A number of specific areas have been studied that are significant for a number of reasons (both pure and applied). Each of these areas (discussed below) has been examined for a specific diode laser: a quantum-well index-guided near infrared (850 nm) device with asymmetric facet coatings. This allows comparisons to be made between the relative effects and manifestations of the different types of feedback on the diode laser behaviour. Such a comprehensive examination for a single type of diode laser has not previously been performed. In addition, the feedback characteristics of several other types of diode laser, including a similar laser device (near infrared quantum-well index-guided) from a different manufacturer, a higher power near infrared broad-area laser diode, and a longer wavelength (1300 nm) quantum-well diode laser with uncoated facets, have been examined and compared.

As the majority of applications require stable (single-mode) operation, the output stability of each laser diode system examined is of primarily importance. Optical feedback, optical injection, phase-conjugate feedback, and frequency modulation are all known to cause instabilities in the laser diode output. These instabilities arise from a range of mechanisms that lead to a range of distinct dynamic states (output power versus time). In general, any deviation from a stable output power causes multi-longitudinal mode operation. While the time dependent output state is important in the field, the current work only considers the spectral stability. Thus, the exact dynamic state is not investigated, but the output stability is inferred from the optical frequency spectrum.

The majority of applications of diode lasers with feedback utilise the strong feedback regime. This regime has attracted less attention in the literature, however, than the low feedback regimes. The vast amount of theory describing diode lasers with feedback is based on a rate equation analysis that is only appropriate to describe weak to moderate feedback levels. Although many experimental papers report effects of strong feedback, there is little systematic investigation into behaviours covering a range of feedback levels. Thus, the
systems studied in the current research all include either strong feedback or a range of feedback levels from weak to very strong.

**Diode lasers with misaligned (asymmetric) optical feedback:**

In many diode laser systems that use strong feedback there are a number of observed characteristics, the underlying physical mechanisms responsible for which are not well known. One such area is the correspondence of the diode laser output state to the angular alignment of the optical feedback field. The motivation for the current work is thus to make experimental observations in order to understand how the alignment of the external reflector effects the output (stability and power) so that the output most appropriate for a given application can be achieved with a specific alignment procedure.

**Diode laser stability versus feedback phase and external cavity length:**

Practical diode laser with feedback systems use a broad range of operating parameters, including external cavity length, injection current, and mechanical stability. It is thus important to understand how these parameters effect the output spectral stability. A number of theoretical investigations describing the stability of a diode laser with feedback as a function of cavity length and feedback phase have been reported [39,64-66,166]. These theoretical models, however, only apply for weak feedback and there is little experimental data at present. The motivation for the current study is thus to make these experimental observations for different types of diode laser, to compare the observations with expectations from existing theories, and suggest possible areas for modification to the theories.

**Diode lasers with optical injection and optical feedback:**

While diode lasers subject to either optical feedback or optical injection have been studied extensively, diode lasers subject to both optical feedback and optical injection simultaneously have attracted limited attention. Previous studies have been concerned with the effects of the injection on such properties as turn-on-jitter [167]. No experimental observations have been reported. The motivation for the current work is thus to report these observations. In particular, the effect of the feedback fraction, feedback system coherence, and the injected power and detuning on the output locking range and coherence state.
1.3. Motivations

**Dynamics of diode lasers with phase conjugate feedback:**

There are a large number of published papers on the modelling of the dynamic behaviour of diode laser with PCF (for example [137,138]). These studies are primarily concerned with routes into chaos and instability for weak to moderate feedback levels. Predictions are made that the dynamics of a diode laser with PCF will be distinct from the dynamics observed with a diode laser with COF. Previous experimental observations on narrow-waveguide diode lasers with PCF have concentrated on specific attributes (such as frequency stability [127] or linewidth narrowing [121]); no systematic investigation or comparison to the case of COF has been reported. The primary motivation for the current research is thus to make these systematic experimental observations and comparisons of the output stability for the two systems, and then to compare these observations with current theories.

**Broad-area diode lasers with optical feedback and phase conjugate feedback**

Broad-area diode lasers generate an increased output power (compared to narrow-waveguide devices) via an increased gain volume. Such lasers typically operate on a high order transverse mode and multiple longitudinal modes. Phase conjugate feedback in broad-area diode lasers has been shown to improve both the spatial and spectral output characteristics [150,151]. The motivation for the current work is to compare the effects of PCF with COF (primarily on the output spectral stability) and then compare the behaviours with those observed for the narrow-waveguide device.

**Frequency modulated diode lasers:**

The ultimate aim of frequency modulating diode lasers is to provide a source with a very broad bandwidth frequency modulated output. Previous studies have reported that optical feedback can be used to enhance the frequency modulation bandwidth of a diode laser. However, this feedback is accompanied by an induced dynamic instability with similar characteristics to the coherence collapsed state observed in diode lasers with optical feedback [168,169]. The onset of this unstable behaviour limits the achievable frequency modulation bandwidth. The motivation for the current study is thus to characterise the frequency modulation behaviour with feedback (in terms of the modulation bandwidth and transition into instabilities) for a range of operating parameters. Specifically, the effects of external cavity length and optical injection are considered.
1.4. Thesis outline

The basic physics of semiconductor diode lasers is discussed in the next chapter. In addition, the general characteristics observed when diode lasers are subject to optical feedback, optical injection, phase conjugate feedback, and frequency modulation, are described. The underlying mechanisms responsible for the range of behaviours are explained and compared in Chapter 2. The experimental results are then presented in the following chapters.

Chapter 3 describes the effects of the angular alignment of the optical feedback field on diode laser operation. It is found that under certain operating conditions the maximum output power from a diode laser with optical feedback is obtained for non-axial alignments of the external plane mirror. This is explained in terms of a spatially dependent coupling coefficient. In addition, different systematic sequences between the spectral content of the output and the axial alignment of the external reflector are observed for two different laser diodes that have been used.

In Chapter 4, the effects of the external cavity length, injection current, and feedback phase on the operating characteristics (output power and stability versus feedback fraction) of diode lasers with optical feedback are considered. Characteristics are examined for two different types of diode laser, which show quite different behaviours. One type of diode shows that optical feedback induced coherence collapse is absent for semiconductor lasers with short external cavities for both strong and weak feedback. Preliminary theoretical models make a number of predictions in qualitative agreement with experimental observations.

In chapter 5, the effects of injection locking a laser diode that is also subject to varying levels of optical feedback from an external reflector are presented. It is found that the locking range of a laser diode with optical feedback is reduced relative to that of a solitary laser diode depending on both the increased photon lifetime and the amount of optical feedback. When the laser diode with feedback is locked in frequency to the external injection source, then coherence collapse and other low optical feedback regimes of operation are suppressed. An extension of this result, to produce a self-locked or master/slave-locked diode laser system that is insensitive to unwanted feedback typically encountered in practical communication systems, is also discussed.

The effects of phase conjugate feedback on the operation of diode lasers are considered in Chapter 6. The process of phase conjugation and its generation in bulk photorefractive crystals is explained. The evolution of the optical frequency spectrum, the
intensity noise spectrum, and the output power with increasing feedback for PCF is investigated and compared to that for COF. It is found that the diode laser with PCF displays different dynamic behaviour than the diode laser with COF. In particular, distinct noise spectra for the two systems at the boundaries between stable and unstable feedback regimes and a temporal evolution of the optical frequency spectrum through a number of distinct states are observed. The experimental observations are compared to current theoretical models that describe PCF, and the implications for various applications are discussed.

In chapter 7, the behaviour of a broad-area diode laser subject to conventional optical feedback is compared to the same laser subject to phase conjugate feedback. It is found that PCF of appropriate strength can force the laser diode to operate on a single longitudinal mode of the broad-area diode; this does not occur for PCF. This single-mode operation, however, consists of a multi-mode operation at the external cavity mode frequency, and an output power that is dynamically unstable. The observed features are compared to the narrow-waveguide observations from the preceding chapter.

Frequency modulated diode lasers subject to feedback and/or injection are investigated in chapter 8. It is found that the modulation bandwidth of a frequency modulated external cavity diode laser (FM ECDL) is suppressed with a short external cavity and enhanced with a long cavity. In addition, optical injection is found to suppress the modulation index and to inhibit the modulation induced coherence collapse that is characteristic of such FM systems. Due to this, larger bandwidths are attainable than for free-running FM ECDLs. Future device and system designs for obtaining very broad optical bandwidth FM operation are presented.

Concluding remarks are given in chapter 9. The main experimental observations are summarised, the implications of these results are discussed, and the direction of future work is outlined. Appendix A tabulates the parameters of each diode laser used in experiments and simulations, appendix B provides a list of symbols, and appendix C lists the publications arising from this research. Following this is a list of references.
Chapter Two: Theory

2.1. Semiconductor diode lasers

2.1.1. Basic laser characteristics

The operating principles of a diode laser are similar to those of any other laser system. The device consists of a gain medium with feedback. Providing the gain is sufficient to overcome the losses in the system then lasing can occur. The first diode lasers were homostructure devices, which consisted of a p-n junction fabricated from only one semiconductor material. They were only capable of pulsed operation at low temperatures and had high threshold injection currents [1-4]. Current semiconductor devices are fabricated with heterostructures that allow room temperature low threshold cw operation. The heterostructure widths can be chosen to produce either a bulk, or a quantum-well gain medium.

A simple heterostructure device, the double heterostructure, which comprises a narrow bandgap, usually p-type, semiconductor material (the active layer) that is placed between two passive sections (one n-doped, the other p-doped), is illustrated schematically in figure 2.1. Gain is provided by the application of a forward biased electric field and feedback is provided from the semiconductor facets. The facets have an uncoated reflectance of ~32% (for GaAs/AlGaAs devices) due to Fresnel reflections; high reflectance or anti-reflectance coatings are often added to improve performance. The forward biased current results in an injection of electrons (from the n-doped layer) and holes (from the p-doped layer) into the active layer. These excess carriers are confined to the active layer by the bandgap differential. They can then recombine via nonradiative recombination, stimulated emission (lasing) or spontaneous emission.

Lateral confinement of the laser field is achieved by gain-guiding or index guiding. In a gain-guided laser the lateral extent of the laser field is determined by the current density distribution with respect to a contact stripe. Injected charge carriers are confined by the specific geometric device design; examples of gain-guided diode lasers include the oxide-stripe laser, the proton-implanted laser, and the V-groove laser (see for example ref [22,170]). In an index-guided laser a refractive index profile fabricated perpendicular to the layer
structure acts as a waveguide to confine the light field (in combination with the charge); examples include the channelled-substrate-planer (CSP) laser, the buried-heterostructure (BH) laser, and the transverse-junction-stripe (TJS) laser (see for example ref [22,171]).

![Image of a double heterostructure diode laser with labels: contact layer, n-doped heterolayer, p-doped heterolayer, active layer, substrate, contact layer.]

**Figure 2.1. Basic structure of a double heterostructure diode laser.**

### 2.1.2. Physics of semiconductor lasers

The basic physics of (bulk gain medium) Fabry-Perot semiconductor lasers can be modelled following a straightforward semiclassical approach. Such an approach (outlined here) allows the basic principals of many of the operating characteristics to be understood. For a more complete treatment, appropriate also to quantum-well laser diodes, see for example ref [170] or Chow et al [171]. The electric field vector, $E$, within the laser cavity is written

$$E = E_0 \exp[i(\omega t - k z)] + E_0^* \exp[-i(\omega t - k z)],$$

where $\omega$ is the angular frequency, and the complex propagation constant $k$ is given by

$$k = n \frac{\omega}{c} - i \alpha_{abs} \frac{2}{\alpha_{abs}}$$

with $n$ the real part of the refractive index, $c$ the speed of light, and $\alpha_{abs}$ the power absorption coefficient (which modifies the refractive index through the pumping mechanism). Using the travelling wave amplifier model, the resonator is considered as a Fabry-Perot cavity consisting of a dielectric medium of length $L$ confined between two mirrors of reflectivity $R_1$ and $R_2$. The forward travelling and backward travelling complex electric fields then yield the condition for stationary laser oscillation

$$\sqrt{R_1R_2} \exp\left[-2i \frac{n \omega}{c} L - \alpha_{abs} L\right] = 1 = G.$$

$$\sqrt{R_1R_2} \exp\left[-2i \frac{n \omega}{c} L - \alpha_{abs} L\right] = 1 = G.$$
This lasing condition gives the optical gain, \( g_{\text{opt},\text{th}} \), at laser threshold

\[
g_{\text{opt},\text{th}} = \alpha_{\text{int}} + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right),
\]

(2.4)

where \( \alpha_{\text{int}} \) is the internal loss factor, and the lasing frequency of the \( m \)th longitudinal mode of the lasing cavity

\[
\omega_{\text{th},m} = \frac{m \pi c}{nL}.
\]

(2.5)

Dynamic analysis of semiconductor laser oscillation is modelled by a set of rate equations. These can derived from the travelling wave amplifier model (which considers the electric field with respect to time), and the electromagnetic wave equation, which describes the propagation of optical fields inside the semiconductor medium [22,25]:

\[
\nabla^2 E - \frac{\sigma}{\varepsilon_0 c} \frac{\partial}{\partial t} E - \frac{1}{c^2} \frac{\partial^2}{\partial x^2} E = \frac{1}{\varepsilon_0 c^2} \frac{\partial^2}{\partial x^2} P_{\text{pol}},
\]

(2.6)

where \( P_{\text{pol}} \) is the macroscopic polarisation, \( \varepsilon_0 \) is the vacuum permittivity, and \( \sigma \) is the surface charge. The travelling wave approach (outlined here) yields the same results as a more rigorous derivation starting from the complete semiconductor Bloch equations and Maxwell’s equations [172,173]. Substitution of the electric field equation 2.1 into equation 2.6, taking account of the dispersion induced change in the dielectric constant, \( \varepsilon \), given by [24,25]

\[
\varepsilon E = \left( \varepsilon(\omega) E_0 + i \frac{\partial \varepsilon}{\partial \omega} \frac{\partial E}{\partial \omega} \right) \exp \left[ i (\omega t - kz) \right] + \text{c.c.},
\]

(2.7)

yields the following rate equations, which describe the temporal change in the electric field amplitude, \( E_0 \), (via the photon number \( P \) and phase \( \phi \)), and the carrier density, \( N \), within the semiconductor active region:

\[
\frac{dP(t)}{dt} = \left( G(N) - \frac{1}{\tau_p} \right) P(t) + R_p + F_p(t)
\]

(2.8)

\[
\frac{d\phi(t)}{dt} = -\frac{\alpha}{2} \left( G(N) - \frac{1}{\tau_s} \right) + F_q(t)
\]

(2.9)

\[
\frac{dN(t)}{dt} = J - \frac{N(t)}{\tau_s} - G(N)P(t) + F_N(t).
\]

(2.10)

\( G(N) \) is the carrier density dependent gain, \( \tau_s \) is the carrier lifetime, \( \alpha \) is the linewidth enhancement factor, \( J \) is the injection current density, and \( F_{P, \phi, N} (t) \) are Langevin noise terms for the photon number, phase, and carrier density, respectively. The Langevin noise terms account for fluctuations of the electric field and phase in the active region due to spontaneous
emission events. They are assumed to be Markovian in nature (delta correlated in time and space), and are described in more detail by Henry [174] and Lax [175]. The cavity loss is described by the inverse photon lifetime, $\tau_p$, defined by

$$
\tau_p = \frac{n}{c} \left( \alpha_{\text{int}} + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) \right)^{-1}.
$$

(2.11)

The spontaneous emission rate $R_{sp}$ is caused by vacuum fluctuations and is described as a randomly occurring increase of unity in the photon number, accompanied by a random change in phase of the optical field. It can be denoted as

$$
R_{sp} = \frac{C_{sp} N}{\tau_s (N)}
$$

(2.12)

where $C_{sp}$ is the fraction of photons that are spontaneously emitted into the active layer (on the order of $10^{-5}$ for typical semiconductor lasers) [176].

The above rate equations (2.8, 2.9, 2.10) have been derived following a number of simplifying assumptions. Firstly, the slowly varying envelope approximation (SVEA) is employed. This relies on the difference in time scales at which the electric field changes in time and space. It is considered that the electric field amplitude $E(t)$ varies slowly compared to the optical carrier frequency $\omega$. In the second order differential equation for the electric field, derived from the electromagnetic wave equation, the second derivatives can be discarded, as they are very small compared with the first order terms:

$$
\frac{d^2}{dt^2} \ll \omega \frac{d}{dt} \ll \omega^2.
$$

(2.13)

This considerably simplifies the theory. Secondly, the polarisation has been adiabatically eliminated. This is possible because the interband polarisation adjusts to changes in the electron and hole distributions (carrier density fluctuations) on a sub-picosecond time scale [21,24]. This is significantly faster than the photon lifetime, and hence fluctuations in the electric field,

$$
\left| \frac{\partial P_{\text{int}}}{\partial t} \right| \ll \gamma_k |P_{\text{int}}|.
$$

(2.14)

where $P_{\text{int}}$ is the interband polarisation. Therefore, as the temporal variation in the carrier density and field amplitude are followed adiabatically by the polarisation, the polarisation term in the wave equation (2.6) can be ignored. This approximation is no longer valid if the photon lifetime becomes comparable to the intraband scattering time, or if the electric field varies substantially within the cavity round trip time.
2.1. Semiconductor diode lasers

The gain is typically described as a linear function of carrier density [22]. This description, however, is not always appropriate. Certain types of diode laser, such as quantum-well devices, require an exponential function [171]. It is also known that at high light intensities the gain will saturate. This is primarily due to spatial hole burning [177], dynamic carrier heating [178], and carrier density dependent dispersion [179-181]. Although diode lasers need to be operated at very high injection currents to notice many effects of nonlinear gain, an accurate theoretical description (as given in refs [177,178,182]) of semiconductor laser dynamic behaviour and spectral features must include it.

Many aspects of the static behaviour of diode lasers can be obtained from steady state solutions of the rate equations, ie \((d/dt=0)\). These include the light current characteristics. The diode laser threshold injection current, \(I_{th}^{dl}\), is found from the carrier density rate equation,

\[
I_{th}^{dl} = eVR(n_{th}),
\]

where \(V\) is the applied voltage, and the recombination rate at threshold \(R(n_{th})\) is determined from the gain at threshold carrier density (equation 2.4). The solitary diode laser external quantum efficiency \(\eta_{ext}^{dl}\) (output from facet 2) is similarly derived:

\[
\eta_{ext}^{dl} = \frac{\ln\left(\frac{1}{R_1 R_2}\right)}{2\alpha_{int} L + \ln\left(\frac{1}{R_1 R_2}\right)} \left(\frac{hf_{0}}{e}\right) \eta_{int},
\]

where \(\eta_{int}\) is the internal quantum efficiency, and \(f_{0}\) is the central lasing frequency.

The output optical frequency spectrum (longitudinal mode structure) of a semiconductor laser is determined by several factors. Due to the high gain available in semiconductor materials, diode lasers can be made very small. Cavity lengths are typically 100 to 1000 \(\mu m\). This results in a very large (compared to other laser devices) longitudinal mode spacing, typically 50-500 GHz, as given by equation 2.5. However, because the transitions are between atomic semiconductor bands as opposed to discrete atomic energy levels the gain bandwidth is also very large (10-100 nm). Hence, there are a large number of possible lasing modes under the gain curve. For a purely homogeneously broadened linear gain medium, only one of these modes can lase. Such a single-frequency output would be ideal for the majority of applications. However, most early semiconductor lasers, and devices of simple construction typically operate on many longitudinal modes simultaneously.

A number of factors determine the longitudinal mode spectrum of the laser emission. These include spontaneous emission, lateral mode confinement, dopant concentrations in the active layer, longitudinal mode coupling, thermal resistance, and inhomogeneous broadening
mechanisms [183]. For single longitudinal mode operation in a diode laser, the waveguiding mechanism must support only the fundamental transverse mode, energy confinement in the active layer must be reduced so that the spontaneous emission factor is decreased, and thermal resistance should be made as small as possible [184,185]. The mechanisms responsible for the influence of other factors on the output mode spectrum, such as facet reflectivities and gain nonlinearities, are not fully understood [186-188].

An important characteristic of diode laser operation is the linewidth enhancement factor, $\alpha$, that appears in the phase rate equation (2.9). This term arises because the real refractive index in the active laser medium, $n$, varies with changing carrier density. Spontaneous emission events induce an instantaneous phase change in the laser field. Accompanying this phase change is an instantaneous change in the laser field intensity, which results in a delayed phase change. In order that the steady state field intensity is restored, the laser undergoes relaxation oscillations, which cause a deviation of the imaginary part of the refractive index, $n''$, from its steady state value. This change is caused by a changing carrier density, which also modifies the real part of the refractive index. The ratio of these fluctuations gives the linewidth enhancement factor [172,189]

$$\alpha = \frac{\Delta n}{\Delta n''}. \quad (2.17)$$

This strong coupling of the carrier density to the refractive index is a characteristic of semiconductor lasers only; $\alpha$ is typically 2-5 for semiconductor lasers [54], and zero for other laser types. It influences many characteristics of diode laser behaviour, such as dynamics, modulation, noise, and linewidth. The relaxation oscillations manifest themselves on the optical frequency spectrum as a set of sidebands separated from the central lasing mode by the relaxation oscillation frequency [190]. This frequency scales as the square root of the output power; typical values near maximum output power are 2-10 GHz [191].

The laser line shape of a semiconductor laser can be approximated by [192,193]

$$S(f) = \frac{1}{1 + \frac{4\pi^2}{R_{sp}}\left(\frac{f - f_0}{f_0}\right)^2 \left(\frac{f - f_0}{f_0}\right)^2}.$$  

(2.18)

This function is a Lorentzian lineshape which has a full-width-at-half-maximum (FWHM) given by

$$\delta f_0 = \frac{R_{sp}}{4\pi P} \left(1 + \alpha^2\right). \quad (2.19)$$
The linewidth is thus proportional to the spontaneous emission rate and to the inverse of the photon number, and is increased proportionally by the square of the linewidth enhancement factor. The linewidth of a solitary semiconductor laser is typically much larger than that of a solid state or gas laser (by a factor of ~50). This is due to the increased phase fluctuations originating from spontaneous emission events, and the increased phase change associated with the laser-field intensity change [44].

2.2. Diode lasers with optical feedback

2.2.1. Characteristics

The effects of optical feedback on the operating characteristics of a diode laser depend on several parameters. These include the level of the feedback in comparison to the diode laser output power, the relative phase of this feedback, the length of the external cavity, and the injection current of the solitary diode laser. It is found that there are five distinct regimes that are defined by the level of the feedback power ratio [44]. This is shown in figure 2.2, below, which also shows typical optical frequency spectra corresponding to each regime. In general, the boundaries between the regimes also depend on the internal parameters of the solitary diode laser, such as the linewidth enhancement factor, the diode dimensions, and the facet coatings. The features of each regime are outlined below. While the behaviour of diode lasers with optical feedback is generally more complicated than presented in this five regime view, it is a good guide for most systems and is useful for categorising and comparing results.

Regime I:

This regime corresponds to very low levels of feedback (less than $10^{-7}$ %). Such levels have the effect of either narrowing or broadening the spectral linewidth (up to 30% [174]) depending on the phase of the feedback. In-phase feedback decreases the linewidth, out-of-phase feedback increases the linewidth [35]. The phase of the feedback within this region also has an effect on the lasing frequency and the threshold gain. Both will either be increased or decreased dependent on the phase. The importance of this regime lies not in the manipulation of linewidths achievable, as greater control can be achieved in higher regimes, but because these effects may inadvertently occur in systems due to unwanted reflections, minor perturbations, and misalignments.
Figure 2.2. Regimes of optical feedback effects, occurring for different values of the external reflectivity and the external cavity length. After [44]. Also shown is an experimental example of a typical output optical frequency spectrum for each regime (at a resolution of ~1000 GHz).

Regime II:

The transition to this regime from regime I is characterised by an observed line broadening (for out of phase feedback) which changes to an apparent splitting of the emission line resulting from rapid mode hopping. This splitting, from a single laser diode mode to a dual mode, is accompanied by a considerable increase in phase noise and intensity noise arising from the different threshold gain associated with each of the two modes. The two modes observed in this regime do not simultaneously exist; the system lases alternately at each one. As the feedback is increased towards regime III the mode hopping frequency and the mode splitting frequency increases.
Regime III:

This regime is characterised by stable single-mode operation. The stability arises because, due to the feedback phase, the mode with the minimum linewidth is the dominant lasing mode; as opposed to the mode with the minimum threshold gain that lases in regime I. The minimum linewidth mode has the best phase stability [26]. This regime occupies only a very small value of feedback power ratios, from 0.01- 0.1%. Due to this small range the laser is very sensitive to other reflections of minor or comparable magnitudes, and may jump to the other relatively unstable regimes II or IV. For this reason regime III is inappropriate for most applications.

Regime IV:

Above a certain threshold level of feedback there is a transition, typically through a series of bifurcations, to a dynamically unstable state. This regime, which is known as coherence collapse, is characterised by a laser linewidth that is broadened by several orders of magnitude (as wide as 50 GHz), operation on multiple solitary diode longitudinal modes, and a broadband intensity noise spectrum [80,194]. The feedback for which this occurs is approximately 1-10%. Measurements of the coherence function of lasers operating in this regime have demonstrated that the coherence length of the laser decreases dramatically, by as much as a factor of 1000 times; this results in coherence lengths less than 10 mm [43]. Due to its large broadband output, this regime is useless for coherent communications. However, applications such as imaging or secure data transmission require highly incoherent sources.

Regime V:

At very strong levels of feedback, the coherence of the laser is regained; this is known as regime V behaviour. This regime is characterised by very narrow-linewidth stable single-mode low intensity noise [194] operation. It corresponds to feedback power ratios of greater than ~10%. In this regime the properties of the external cavity system are generally assumed to be determined by the external cavity rather than by the laser diode; it operates as a long cavity laser with a short active region. Experimentally it is usually required to anti-reflection coat the diode laser front facet in order to reach this regime. Due to the strong feedback in this regime the system is also much less sensitive to additional reflections. The system operating in this regime is often referred to as an external cavity diode laser (ECDL) system.
2.2.2. Physics of diode lasers with optical feedback

The physical processes that lead to the range of different behaviours observed in the presence of feedback are varied and complex. The important effects caused by the feedback are the increased side mode suppression, decreased linewidth, and decreased threshold gain observed in regimes I, III, and V; the dynamic transitions to chaotic operation from regime III to regime IV; and the dynamic state of low frequency fluctuation observed at the boundaries of regime IV. The mechanisms responsible for each of these features are discussed below.

Side Mode Suppression and Linewidth Reduction:

As discussed in section 2.1.2 various mechanisms are responsible for producing single-frequency operation in a semiconductor diode laser. In the presence of appropriate feedback levels (regimes I, III, and V) a solitary diode laser that operates on multiple longitudinal modes is forced to operate on a single-mode. If the solitary diode laser operates predominantly on a single-mode then the feedback has the effect of suppressing the side modes. Although a grating can be used to provide frequency selective feedback and to enhance side mode suppression, single-mode operation can be achieved with feedback from a plane mirror (with a specific reflectivity). This implies that the wavelength selectivity provided by the grating is not the primary cause of single-mode output [53].

A combination of factors induces single-mode operation in a semiconductor laser with feedback [184]. The first is transverse mode control. The phase control introduced by the geometry of an external cavity laser diode forces the laser to operate in the fundamental transverse mode; this is necessary for effective longitudinal side mode suppression [195]. The second is thermal resistance i.e., how the oscillation frequency changes due to temperature fluctuations; diode lasers with optical feedback show much lower thermal resistance than solitary diode lasers. Most important is the spontaneous emission factor; external cavity systems usually exhibit small spontaneous emission rates in each longitudinal mode [174]. Another important factor that leads to single-mode operation, particular in long cavities, is longitudinal mode coupling. This arises from interference terms in the stimulated emission rate. This interference is effective in an external cavity laser because of spatial coincidence of the field amplitudes in the semiconductor cavity [196]. There is also evidence that spatial and spectral hole-burning can be reduced in the presence of feedback [44]. This can reduce the effect of nonlinear gain saturation.
Modification to the linewidth by the application of optical feedback, which is either a
decrease or increase in regime I, or a decrease in regime III, and V, occurs due to a reduction
in the two line broadening mechanisms. The external cavity firstly reduces the spontaneous
phase fluctuations (by approximately five orders of magnitude [192]), and secondly it
decouples the resonant laser frequency from the strong dependence on the semiconductor
refractive index [197]. The output phase and intensity noise is also reduced [30,190].

**Slope efficiency and threshold gain:**

The threshold gain and slope efficiency equations (2.15, 2.16) for a solitary diode laser
are valid for a diode laser with optical feedback when the output (front) facet reflectivity, \( R_2 \),
is replaced by an effective reflectivity, \( R_{eff} \), which accounts for the output facet coupled to the
external cavity. This assumption is only appropriate for weak feedback levels; ie the model
only considers a single round trip of the external cavity, and multiple round trips due to extra
reflections are ignored.

\[
R_{eff} = \frac{r_2 + r_3 \exp\left(\frac{i2\omega l}{c}\right)}{1 + r_2 r_3 \exp\left(\frac{i2\omega l}{c}\right)} \tag{2.20}
\]

where
\[
r_3 = \sqrt{\eta_c R_{ext}}, \tag{2.21}
\]
\[
r_2 = \sqrt{R_2}, \tag{2.22}
\]

\( l \) is the external cavity length, \( R_{ext} \) is the external feedback fraction (the ratio of the feedback
power to the output power in front of the diode), and \( \eta_c \) is the coupling efficiency between the
external feedback field and the diode laser active layer. If the length of the external cavity is
longer than the coherence length of the diode laser and collimating optic then the effective
reflectivity does not vary with external feedback phase, and may be described by its
maximum value,

\[
(R_{eff})_{max} = \left| \frac{r_2 + r_3}{1 + r_2 r_3} \right|^2. \tag{2.23}
\]

The coherence length of a collimated diode laser can be estimated by examining the effect of
phase on the output power at a range of external cavity lengths. Typical values quoted in the
literature range from 10-200 cm, dependent on the particular diode laser used [198]. The slope
efficiency (output from the facet (2) facing the feedback field) of a diode laser with optical
feedback can be described by [170]
\[
\eta_{\text{ext}} = \eta \left( \frac{1 + r_2 r_3}{r_1 (r_2 + r_3)} \right)^2 \left( \frac{h f}{e} \right) \eta_{\text{int}} .
\] (2.24)

The threshold gain and phase conditions are similarly modified by the presence of feedback, which results in a change in the threshold injection current of the system. The ratio of the threshold injection current of the solitary diode laser, \( I_{\text{th}}^{\text{dl}} \), to the threshold injection current of the diode with external optical feedback, \( I_{\text{th}}^{\text{ex}} \), can be approximated by [51]

\[
\frac{I_{\text{th}}^{\text{ex}}}{I_{\text{th}}^{\text{dl}}} = 1 + 2 f_d \tau_p \ln \left( r_s \frac{1 + r_2 r_3}{r_2 + r_3} \right),
\] (2.25)

where \( f_d \) is the longitudinal mode spacing of the solitary diode.

Feedback is thus seen to have a dramatic effect on the light versus current characteristics of a diode laser. Both threshold and slope efficiency are significantly reduced by amounts dependent primarily on the level of feedback but also on various parameters of the solitary diode. These include the internal loss, internal quantum efficiency, facet coatings, length and mode spacing, and the efficiency of the coupling between the diode laser and the external feedback field. The relationship between the feedback field (in particular its alignment with respect to the diode laser output field) is examined in more detail in chapter 3.

**Dynamic Instabilities:**

The transition from the stable single-mode regime III to the chaotic regime IV can be theoretically modelled by a dynamic rate equation analysis. The rate equations that describe the solitary diode laser (2.8, 2.9, 2.10) are modified to account for optical feedback by including feedback terms in both the photon number and phase equations. These modified rate equations are known as the Lang-Kobayashi rate equations:

\[
\frac{dP(t)}{dt} = \left( G(N) - \frac{1}{\tau_p} \right) P(t) + R_{sp} + F_p(t)
\]

\[
+ 2 \kappa \sqrt{P(t) P(t-\tau) \cos(\omega_o \tau + \phi(t) - \phi(t-\tau))}
\] (2.26)

\[
\frac{d\phi(t)}{dt} = -\frac{\alpha}{2} \left( G(N) - \frac{1}{\tau_p} \right) + F_\phi(t)
\]

\[
+ \kappa \sqrt{P(t-\tau) \sin(\omega_o \tau + \phi(t) - \phi(t-\tau))}
\] (2.27)
\[
\frac{dN(t)}{dt} = J - \frac{N(t)}{\tau_s} - G(N)P(t) + F_N(t),
\]

(2.28)

where \( \tau \) is the external cavity round trip time. The coupling coefficient \( \kappa \), for the case of weak feedback, is given by

\[
\kappa = \frac{1}{\tau_{in}} \sqrt{\eta_e R_e} \frac{1 - R_e}{R_i}
\]

(2.29)

where \( \tau_{in} \) is the solitary diode internal round trip time.

The above rate equations give intuitive understanding of the reasons that instabilities occur in diode lasers in the presence of feedback. It is known from nonlinear dynamic theory [199,200] that for a system to display nonlinear dynamics that lead to chaotic instabilities it must be described by three coupled first-order nonlinear differential equations. The solitary semiconductor diode laser is described by three nonlinear differential equations but they are not fully coupled; the phase is merely a slave variable of the photon number, and not coupled to the carrier density. Therefore, instabilities and chaotic behaviour are not observed with a solitary diode laser. The feedback terms in equations 2.26, and 2.27 have the effect of coupling the phase to both the photon number and the carrier density. This introduces infinite degrees of freedom to the system, allowing and predicting the development of chaotic dynamics. Solutions of the rate equations provide information about such dynamics [25].

Figure 2.3. Schematic of attractors in the \((E_0, \Delta, N)\) space for a feedback level in regime IV. Triangles represent antimodes and crosses represent fixed points that have become unstable through bifurcations. After [40].
The solution of the three equations describes a trajectory in three-dimensional space; for example \((E_0, \Delta \phi, N)\). The particular trajectory is termed an attractor, and it contains information about the system’s dynamic state for a particular control parameter. A schematic example showing a range of possible attractors is shown in figure 2.3. Such attractors are often represented by two-dimensional Poincare sections (the intersection points of an attractor with a transverse plane). The attractor can either be a fixed point, which represents a stable (constant) output power; a limit-cycle, which represents a periodic oscillation of the output power; a torus, which represents a quasi-periodic output power, or chaotic, which represents an output power which is fluctuating chaotically [40].

Examples of theoretically predicted output powers for various solutions are shown in figure 2.4. A periodic (limit-cycle) state is shown in (a); typically this first periodic orbit represents an oscillation at the relaxation oscillation frequency of the solitary diode, as the relaxation oscillation becomes undamped by the feedback [77]. A quasi-periodic state (torus solution) is shown in 2.4 (b); such a state occurs at a higher feedback level and represents periodic oscillation at the relaxation oscillation frequency being modified by the external cavity longitudinal mode frequency. Figure 2.4 (c) shows a chaotic output power.

![Figure 2.4](image.png)

*Figure 2.4. Theoretical predictions of the output power as a function of time for a diode laser with increasing levels of feedback. Three different dynamic states are shown. After [40].*

The evolution of the output dynamic state with increase in a control variable, most commonly the feedback fraction, is illustrated by bifurcation diagrams in theoretical simulations. An example of a bifurcation diagram representing the onset of chaotic behaviour is shown in figure 2.5. For low feedback fractions \((< 0.008)\) the diagram shows that the output power is constant; representing regime III behaviour. At a feedback fraction of approximately 0.008 there is a bifurcation from this stable state to a higher ordered dynamic
2.2. Diode lasers with optical feedback

The output power initially cycles through two different output powers (limit 1) before bifurcating into a higher still dynamic state where the output power cycles through six different levels (feedback fractions 0.009-0.012). Further bifurcations then occur until there is fully developed chaos for feedback fractions above 0.013. The series of bifurcations represents the boundary between regimes III and IV. Fully developed chaos represents regime IV or coherence collapsed behaviour.

Various routes to chaos have been observed theoretically and experimentally, such as periodic, quasi-periodic, and period doubling. The exact route and feedback levels at which transitions occur depend on a number of factors, including imprecisely known parameters for the solitary diode laser (internal loss, internal quantum efficiency, linewidth enhancement factor). For this reason, quantitative agreement between experiment and theory is difficult to achieve. Qualitative agreement, however, has been demonstrated in some studies [40].

![Bifurcation diagram representing the transition from stable single-mode behaviour into chaotic instability. After [40].](image)

Models based on the above equations rely on a number of simplifying assumptions and their validity is limited by several conditions. Langevin noise terms and the effects of spontaneous emission are often ignored to separate the deterministic effects from the stochastic, though a full dynamic analysis would include them. The effect of nonlinear gain suppression is generally negligible for steady state properties but may be important for stability conditions. As only one round trip is considered in the equations, they are generally regarded as being applicable for diode lasers without facet coatings and for low to moderate
levels of feedback from the external mirror. An upper limit on their applicability to feedback levels is $\sim 1.1\%$ [201]. For anti-reflection coated diode lasers, the constraint on multiple round trips is lessened. However, there is also a requirement that the dynamic change in the complex wave number is small, i.e. $\Delta k L \ll 1$, with $L$ the solitary diode length. This condition is violated at high feedback levels in the coherence collapse regime and above. A number of methods have been used to examine the behaviour of diode lasers coupled to strong feedback. These are generally derived from a travelling wave description of the system, and include iterative [202,203] and composite-cavity approaches [52,179,204]. An experimental examination of dynamic states inferred from the optical frequency spectrum and intensity noise spectrum is presented in chapter 6.

**Low Frequency Fluctuations:**

Optical feedback into semiconductor diode lasers has been observed to induce a specific type of instability, known as low frequency fluctuation (LFF), which is not observed in any other kind of laser. In the LFF state, the average laser power shows sudden drops in intensity, which gradually recover, before dropping out again after some unfixed time. This is shown in figure 2.6 (a), below. The average time between power drop-outs is typically 5-20 times the external cavity round trip time. On a much faster (sub nanosecond) time scale there is an irregular train of intensity pulses within the envelope of drop-out events. The pulse durations are on the order of several hundred picoseconds, as shown in figure 2.6 (b).

The phenomenon of LFF has been theoretically modelled, and many features are adequately described by a Lang-Kobayashi rate equation analysis [49,205]. Theoretical predictions of the output power versus time in the LFF regime demonstrate good qualitative agreement with the experimental observations. The LFF state is a dynamic instability (a time inverted type II intermittency [199]) originated by the merging of an attractor ruin of an external cavity mode with an anti-mode [49,206].

LFF is generally found to exist close to the solitary diode laser threshold, but is also found at higher pumping powers. It has been experimentally observed at the boundary between regimes IV and V [48], and between the III to IV boundary [47]. Typically an increase in injection current at a given feedback fraction shifts the LFF state into fully developed coherence collapse (chaos) [207]. An inverted LFF state, where rapid power increases are followed by gradual decrease in power [48], and regimes of stable single-mode output inside LFF regions [207], have also been observed. The LFF state is accompanied by multi-mode operation on the solitary diode laser frequencies [50], and increased intensity
noise at low frequencies [208]. An LFF state has also been induced by direct frequency modulation of a diode laser with optical feedback [209].

Low frequency fluctuations observed for diode lasers with phase conjugate feedback and conventional optical feedback are discussed in chapter 6.

![Figure 2.6](image.png)

Figure 2.6. Experimental data of average output power versus time for a diode laser operating in the low frequency fluctuation state. Recording bandwidths are 1 GHz in (a) and 50 GHz in (b) for identical experimental conditions. After [210].

### 2.3. Diode lasers with optical injection

Similar to the case of optical feedback, a dynamic analysis of a diode laser subject to optical injection is achieved via the semiconductor rate equations. These are modified to account for the interaction of the slave laser electric field with the electric field of the master laser, within the slave laser active layer. These equations are derived from the van der Pol equations, which describe the process of injection locking in electrical oscillators [85,89].

\[
\frac{dP(t)}{dt} = \left( G(N) - \frac{1}{\tau_p} \right) P(t) + R_{ip} + F_p(t) \\
+ 2f_d \sqrt{P(t)P_{inj}(t)} \cos(\phi(t) - \phi(t)) 
\]  
(2.30)
Chapter Two: Theory

\[ \frac{d\phi(t)}{dt} = \omega_0(N) - \omega_{\text{inj}} - \alpha \left( \frac{G(N)}{2} - \frac{1}{\tau_p} \right) + F_\phi(t) \]

\[ + f_d \sqrt{\frac{P_{\text{inj}}(t)}{P(t)}} \sin(\phi_i(t) - \phi(t)) \]  \hspace{1cm} (2.31)

\[ \frac{dN(t)}{dt} = J - \frac{N(t)}{\tau_s} - G(N)P(t) + F_N(t) \]  \hspace{1cm} (2.32)

where \( \omega_0(N) \) is the angular optical frequency of the slave laser cavity mode, \( P_{\text{inj}} \) is the injected signal power (inside the diode laser active layer), \( \omega_{\text{inj}} \) is the angular optical frequency of the injected signal, and \( (\phi_i(t) - \phi(t)) \) is the phase difference between the injected and the free-running laser fields.

Solution of the above rate equations yields the dynamic state of the slave laser dependent on the injected signal power and detuning. A typical experimental map of behaviours in this parameter space is shown in figure 2.7. A number of different output states are observed. These include four-wave-mixing, injection locking, limit cycle behaviour, chaos, period doubling, and quasi-periodicity.

Figure 2.7: Map of dynamic output states for a diode laser subject to optical injection in the parameter space of injection power and detuning (\( \Delta f \)) between the free-running slave laser frequency and the injection frequency. The labelled regions correspond to S: injection locking, M: multiwave mixing, SR: subharmonic resonance, P1: limit-cycle, P2: period doubling, and P4: period quadrupling. After [109,110].
2.3. Diode lasers with optical injection

Strong Injection:

The externally injected signal from the master laser is regeneratively amplified inside the slave laser diode cavity and produces an amplified output power at the injected frequency. The amplification of this signal increases as it moves closer to the free-running frequency of the solitary diode (maximum of the gain curve). If the frequency detuning between the slave and master lasers is made small enough, or the injected signal power large enough, then the amplified injected signal begins to saturate the laser gain, and the free-running laser oscillation is turned off, leaving only the amplified injected signal. Such a state is known as injection locking; the slave laser is forced to oscillate at the injected signal frequency and is locked to its phase. The range of master laser frequencies over which such a locked state occurs (the locking bandwidth) increases with increased injected signal power [176]. This is the dominant state for strong signal injection, ie when the injected signal power is comparable with the diode laser output power. The injection locked state enhances many of the solitary diode lasers operating characteristics. It suppresses mode hopping, lowers mode partition noise [211], narrows the linewidth [212], increases the side mode suppression, reduces relaxation oscillation under direct modulation [97,98], and can be used to synchronise laser signals (for communications) [62].

The locking range as a function of injected power can be predicted from steady state solutions of the rate equations. When \( \omega(N) = \omega_{inj} \) then the locking bandwidth is represented by [85]

\[
\Delta f_{IL} = \frac{c}{4\pi n L} \sqrt{\frac{P_{inj}}{P_{out}}} (\sin \theta - \alpha \cos \theta)
\]

(2.33)

where \( P_{out} \) and \( P_{inj} \) are the output and injected signal powers, respectively. The optical injection results in a cavity frequency shift, due to the carrier density dependence on the refractive index. This, coupled with the forced oscillation of the slave laser frequency competing with spontaneous emission, results in the predicted locking range being bounded by two values [94]

\[
\frac{c\sqrt{1 + \alpha^2}}{4\pi n L} \sqrt{\frac{P_{inj}}{P_{out}}} \geq \Delta f_{IL} \geq \frac{c}{4\pi n L} \sqrt{\frac{P_{inj}}{P_{out}}}
\]

(2.34)

The strong dependence of the carrier density on the refractive index in the active region also results in a large asymmetry in the locking curve, ie the system more readily locks for positive detuning, as opposed to negative detuning; where positive detuning is defined for an injected signal frequency that is larger than the solitary diode laser free-running frequency. Reasonable quantitative and qualitative agreement between experiment and theory exists in
terms of the locking range predicted by this equation from a number of sources [85,92,93,95,102]. An extension of this model predicting locking ranges to include the effects of optical feedback is described in Chapter 5, and compared with experimental results.

**Weak Injection:**

A dynamic analysis of the rate equations (2.30-2.32) predicts that there are various dynamic instabilities induced by the optical injection field. For a weak signal injection, when the master laser signal is much lower than the slave laser power, the dynamic states are dominant over the injection locked state, as shown in figure 2.7. These instabilities are brought about via a similar mechanism to that for diode lasers with optical feedback [25]. That is, the injection acts to couple the phase to the photon number and hence the carrier density. This, coupled with the competing oscillation fields of the master and slave lasers, leads to the initial undamping of the relaxation oscillation frequency of the slave laser, which causes periodic oscillation of the output power and eventually chaotic behaviour. The main difference between feedback induced instabilities and injection induced instabilities is that there is no competing frequency (of the external cavity) for optical injection. There is, however, a competing frequency of the detuning between the master and slave laser frequencies [84,109].

A range of different dynamic output states are observed, such as period doubling, period quadrupling, limit-cycle behaviour, and chaos [108]. The regions of unstable behaviour are generally much larger than the regions of locking or other stable output as shown in figure 2.7. Qualitative agreement between the theoretical predictions and experimental observations in terms of the range of output dynamic states and relative size has been demonstrated [110]. However, quantitative agreement is again difficult to achieve because of the very large experimental parameter space (detuning, injection to slave power ratio, and slave laser injection current), due to the difficulties in matching the gain bandwidth, and because of imprecisely known variables in the rate equations (as is the case for optical feedback).

**Four-wave-mixing**

The phenomenon of four-wave-mixing in semiconductor diode lasers is a frequency conversion process. It involves the interaction of the slave laser (pump) beam of frequency $f_0$, with the injected signal (or probe) beam of frequency $f_{\text{inj}}$ inside the semiconductor material, which is nonlinear. The interaction of these counter-propagating beams inside the material
2.3. Diode lasers with optical injection

generates a temporal polarisation field inside the semiconductor cavity. This arises due to a
temporal refractive index grating, which builds up from the distribution of light intensity
inside the cavity arising from the interference of the pump and probe waves. A new wave of
frequency $f_c = f_0 - f_{inj}$ is generated from the interaction of the injected probe waves and the
refractive index grating. This new wave is the phase conjugate of the injected signal [86]. The
output of the slave laser will thus consist of three different frequencies, $f_c, f_0,$ and $f_{inj}$. This is
illustrated in figure 2.8, which shows the output optical frequency spectrum of a diode laser in
the process of collinear four-wave mixing. Generally, four-wave-mixing is only attainable for
a weak injected signal [111]. The slave, injected, and conjugate beams are marked. Cascade
conjugate frequencies can also be observed. The frequency detuning of the injected frequency
to the slave frequency is 2.6 GHz.

Figure 2.8. Optical frequency spectrum of a diode laser in the process of collinear
four-wave-mixing. The slave ($f_0$), injected ($f_{inj}$) and conjugate ($f_c$) frequencies are
indicated in the figure.

Although a phase conjugate signal is generated in a narrow-waveguide diode laser, it
is not a true conjugate wave [112]. A narrow-waveguide diode laser only supports one spatial
transverse mode (the fundamental mode). All spatial information of the input probe beam is
lost as it is coupled into this mode. Thus, the frequency-shifted wave generated is a temporal
conjugate only. That is, it can be used, for example, for spectral inversion [116-118]. It is
unclear whether the spatial confinement of the single-mode slave laser is the cause of the loss
of spatial information or whether spatial information is lost because the wave interference
occurs only in one dimension, ie a temporal wave mixing process that generates a temporal
conjugate. Phase conjugation via four-wave-mixing in a broad-area diode laser [213,214] may occur due to a combination of both spectral and spatial interference and thus may generate a spatial (and temporal) conjugate.

The four-wave mixing process can be achieved by injecting the signal close to the central mode of the slave laser, which is termed nearly degenerate four-wave-mixing (NDFWM), or intramodal injection. Alternatively, the injected frequency can be tuned close to a side mode of the slave laser. In this case, the process is known as highly-degenerate-four-wave-mixing (HDFWM), or intermodal injection [114]. Due to the difficulties in matching two diode laser frequencies (within several GHz) intermodal injection is preferred when the master is not a tunable source.

2.4. Diode lasers with phase conjugate feedback

The rate equations that describe a diode laser with phase conjugate feedback are very similar to the Lang-Kobayashi rate equations describing a diode laser with conventional optical feedback. The exact set of equations also depends on the type of phase conjugate mirror that is used.

\[
\frac{dP(t)}{dt} = \left( G(N) - \frac{1}{\tau_p} \right) P(t) + R_p + F_p(t)
\]

\[
+ 2 \kappa \sqrt{P(t)P(t-\tau)} \cos(\phi_{PCF} + \phi(t) + \phi(t-\tau))
\]  

(2.35)

\[
\frac{d\phi(t)}{dt} = -\frac{\alpha}{2} \left( G(N) - \frac{1}{\tau_p} \right) + F_\phi(t)
\]

\[
+ \kappa \sqrt{\frac{P(t-\tau)}{P(t)}} \sin(\phi_{PCF} + \phi(t) + \phi(t-\tau))
\]  

(2.36)

\[
\frac{dN(t)}{dt} = J - \frac{N(t)}{\tau_s} - G(N)P(t) + F_N(t)
\]  

(2.37)

The differences between these equations and those for COF occur in the phase terms for the photon number and phase. A constant phase shift \(\phi_{PCF}\) at the PCM is used instead of the external cavity round trip phase shift, \(\omega\tau\), introduced for COF. \(\phi_{PCF}\) is typically given the value 2\(\pi\) because in an ideal phase conjugate feedback beam there is no phase shift at the semiconductor front facet [141,143]. The coupling coefficient, \(\kappa\), has the same form as for the
COF case (equation 2.29) but the coupling efficiency $\eta_c$ is replaced with the phase conjugate coupling efficiency $\eta_{pcf}$. It is generally considered to have a higher value for PCF because the profile of the conjugate beam is better phase matched to the diode laser output than a reflected beam (for COF) [146].

The same simplifying assumptions that were used to model COF are used in the PCF analysis, ie low feedback and equal facet reflectivities. Additionally, further approximations relate to the specific nature of the conjugate process. The penetration depth of the PCM is generally considered zero in theoretical treatments. This is a measure of the time taken for the incident beams to penetrate inside the PCM in order to generate the phase conjugate signal. Thus, it may rely on factors such as the PCM size and geometry. In order to model this effect, a fourth equation must be added to the rate equations describing the temporal variability of the reflectivity of the phase conjugate beam. This equation can be described by [144]

$$r_{pcm}(x) = \frac{\Gamma}{n} \frac{t_m}{t_m(x+i)}$$  \hspace{1cm} (2.38)

(for non-degenerate four-wave-mixing) where $t_m$ is the time it takes light to penetrate inside the PCM ($t_m \approx nL_{nm}/c$) and $x$ is the detuning of the pump from the probe frequencies ($x \equiv f - f_0$). Secondly, it is generally assumed that the PCM responds instantaneously to the incident light fields. This is only a valid assumption for certain types of PCM, such as Kerr media, which have rapid response times (~ 1 ps). For photorefractive ferroelectrics (such as BaTiO$_3$) and sillenites, which respond quite slowly (~100 s) to incident radiation due to their low carrier mobilities, the PCM response time is slower than the round trip time and thus $\kappa$ becomes time dependent. The material’s response time must then be included in the expression for $r_{pcm}$ (equation 2.38). For conjugation generated in semiconductor media the assumption is more valid as the semiconductor PCM response time, though finite, is similar to the carrier lifetime of the semiconductor laser (~ 1 ns). Further modification to the equations is necessary if the phase conjugate beam is generated from a non-degenerate four-wave-mixing process. In this case, the feedback beam is frequency shifted from the output beam, and an extra term must be added to account for this frequency detuning. This is not necessary for a self-pumped phase conjugate mirror.

Theoretical analysis of these rate equations has shown that qualitative and quantitative changes in various aspects of the laser dynamic behaviour are introduced for PCF as compared with COF; due to the different coupling efficiencies and phase terms [137-141]. Similar to COF the dynamic behaviour is typically explored via bifurcation diagrams and noise spectra obtained from solutions of the Lang-Kobayashi rate equations modified for PCF,
for ranges of external reflectivities and cavity lengths. Shown in figure 2.9 is an example of a theoretical prediction of the bifurcation sequence for a diode laser with COF compared to that for PCF. The same parameters for the solitary diode laser and the external cavity length are used in each case. In this example the diode laser with COF is seen to evolve simply into chaos, and the output is stable over a wide range of the feedback parameter $\kappa \tau$. For PCF the output becomes unstable for low values of $\kappa \tau$, and the chaotic regions are much wider and are interrupted by periodic states.

Figure 2.9. Bifurcation diagrams comparing (a) COF to (b) PCF for similar external cavity length and solitary diode internal parameters. After [141].

Period doubling, quasi-periodic, and intermittency routes to chaos have all been observed. As was the case for COF, the routes to chaos and the feedback levels at which transitions between dynamic states occur depend on a number of the system parameters. Important parameters include the control variables (injection current, external cavity length and feedback fraction), characteristics of the solitary diode (size, wavelength, construction, facet coatings, and relaxation oscillation frequency and damping rate), and properties of the PCM [138,141,142]. Again, many of these parameters are difficult to know precisely, and for these reasons, it is difficult to obtain accurate quantitative agreement between theory and experiment. In addition, small changes to the (diode laser) internal parameters in the theoretical models can drastically effect the predictions. No experimental studies have examined the dynamics directly. They are generally inferred from the output stability (of the optical spectrum), which is found to be altered dependent on the feedback level [134,135].

Similar to COF, phase conjugate feedback has the effect of increasing the side-mode-suppression of the solitary laser diode, forcing a multi-mode diode to operate in a single longitudinal mode, and reducing the slope efficiency and threshold operating current. The
2.4. Diode lasers with phase conjugate feedback

The magnitude of these effects is similar for the two systems. The PCF system is also known to operate in distinct feedback regimes, and multi-mode operation indicative of coherence collapse has been experimentally observed [120,133].

There are, however, several advantages of PCF over COF. Firstly, PCF is found to influence the intensity noise and the frequency noise of the solitary diode laser [146,149]. Predictions of the phase and frequency noise for PCF compared to COF are shown in figure 2.10, above. For certain input parameters the low frequency phase and frequency noise is predicted to be significantly lower for PCF than for COF. Secondly, PCF can be used to provide improved frequency stability [127,129,131], and mode-locking [130-132]. Thirdly, the phase locking characteristics of the PCF produce a modified spectral lineshape of the laser. It has been demonstrated that operation of a diode laser with phase conjugate feedback within a stable regime can result in narrowing the solitary diode linewidth, and that this narrowing is greater than that achievable with feedback from an ordinary mirror [123,127]. The linewidth due to spontaneous emission is drastically reduced because the laser phase is locked and hence the phase variance is saturated. In practice, however, the magnitude of line narrowing is governed by noise sources other than the spontaneous emission inside the cavity, because these noise sources are greater. The limit of linewidth reduction is provided by the linewidth of the laser used to pump the PCM; thus illustrating the advantage of a self-pumped phase conjugate mirror. The PCF also effects the lineshape because the damping rate and frequency of relaxation oscillation is reduced for an increasing feedback level. This, combined with the increased peak in the frequency noise spectrum has the effect of increasing
the satellite peaks with feedback. When the feedback reaches a certain level the satellite peaks become comparable with the central peak, and the output becomes unstable or chaotic, as described above.

Phase conjugate feedback can also be used to enhance many of the spatial properties of the diode laser. Phase conjugation is used in many high-power laser systems for aberration correction. Similar mechanisms are responsible for improving output beam profiles of semiconductor lasers and for enhanced coupling between two or more diode lasers. This is important for two different types of laser diode: broad-area diode lasers and laser diode arrays. Both these devices typically have very poor spatial output profiles, and support many longitudinal modes. Phase conjugate feedback has been demonstrated to improve both the spatial and spectral properties of these devices [150,151], as illustrated in figure 2.11, below. Phase-conjugate injection locking, where a double phase conjugate mirror is used to couple the signal from a master laser, which is a single-frequency tunable device, into the slave laser cavity, which is typically a broad-area laser or laser-diode array, results in improved coupling efficiency between the two lasers (compared with conventional injection locking) [159,162,215,216].

An experimental study of the effects of phase conjugate feedback on narrow-waveguide diode lasers compared to COF is presented in chapter 6. Phase conjugate feedback in broad-area diode lasers is investigated in chapter 7.

![Figure 2.11. Far field profile for a laser diode array free-running and with phase conjugate feedback. After [163].](image)
2.5. Frequency modulated diode lasers

Frequency modulated output (FM lasing) from a diode laser is achieved by applying a periodic modulation to the phase of the electromagnetic field. This can be done either directly (via a modulation of the diode laser current) or indirectly (via an external phase modulating element). Direct modulation is possible in semiconductor lasers due to the strong coupling of the semiconductor refractive index to the carrier density (by virtue of the linewidth enhancement factor). Thus, variations in the injected current in the laser diode yield variations in the carrier density, which leads to variations in refractive index and hence emission frequency and output phase. This carrier effect is the dominant mechanism for modulation frequencies above 10 MHz; thermal effects are also important for lower modulation frequencies [176]. As the injection current is modulated there is also an accompanying modulation of the output power (ie amplitude modulation). The ratio of the frequency modulation to the intensity modulation is dependent on the modulation frequency and the linewidth enhancement factor [22]. Indirect modulation can be obtained by the addition of an external modulating element, such as nonlinear electro-optic crystal, or acousto-optic element, though only low modulation powers are possible in a single pass through the modulator.

An electromagnetic wave with a periodic modulation of the phase can be represented by

\[ E = E_0 \exp\left[2\pi f_m t + \beta \sin(2\pi f_m t)\right] \]

(2.39)

where \(f_m\) is the modulation frequency and \(\beta\) is the modulation index, which is given by

\[ \beta = \frac{\Delta F}{f_m}, \]

(2.40)

where \(\Delta F\) is the maximum frequency deviation. The field spectrum of equation 2.39, can be expanded in terms of Bessel functions \(J_1(\beta)\) of the first kind

\[ E = J_0(\beta)E_0 \sin(2\pi f_0 t) + J_1(\beta)E_0 \sin\{2\pi (f_0 + f_m) t\} \]

\[ - J_1(\beta)E_0 \sin\{2\pi (f_0 - f_m) t\} + \ldots + J_n(\beta)E_0 \sin\{2\pi (f_0 + nf_m) t\} \]

\[ + (-1)^n J_n(\beta)E_0 \sin\{2\pi (f_0 - nf_m) t\}. \]

(2.41)

The optical frequency spectrum of such a frequency modulated wave thus consists of the centre lasing carrier frequency and a series of sidebands separated by the modulation frequency. The first few lower order Bessel functions are shown in figure 2.12, representing the relative amplitudes of the sideband pairs for an increase in modulation index. All frequencies are not present simultaneously; the output frequency sweeps through the comb of
modes at the modulation frequency [217,218]. The accompanying intensity modulation manifests itself as an asymmetry in the sideband pairs [219].

![Bessel function amplitudes for the first four sidebands.](image)

**Figure 2.12.** Bessel function amplitudes for the first four sidebands. After [220].

The resulting output from a frequency modulated laser is known as FM laser operation; it was first demonstrated in a HeNe laser in 1964 [217], and in a diode laser in 1982 [219]. Increasing the modulation power, which represents the level of the modulation current relative to the dc injection current for direct modulation, and the drive current to the phase modulating element for indirect modulation, has the effect of linearly increasing the modulation index of the output spectrum [221]. For gas lasers large modulation bandwidths are attainable simply by increasing the modulation power (usually bounded by damage thresholds in modulator elements). For semiconductor diode lasers, however, as the modulation power is increased (at any particular modulation frequency) a threshold is reached beyond which dynamic instabilities occur [222]. The mechanisms responsible for such dynamic behaviour are similar to those responsible for instabilities introduced by the presence of optical feedback or injection. That is, the modulation of the internal phase couples the three internal laser parameters: phase, carrier density, and photon number, which allows the development of (eventually) chaotic output power [25]. This manifests itself on the optical field spectrum as a multi-longitudinal mode state. Additionally, at higher modulation powers the amplitude modulation begins to dominate over the frequency modulation, generating highly asymmetric frequency mode profiles. Generally, only low modulation indexes (<10) are possible with modulated solitary diode lasers [221].

One way of increasing the modulation index (bandwidth) at a given frequency is by introducing optical feedback [223,224]. This introduces a resonant frequency, \( f_{ex} \) (the external cavity mode spacing), to the system [24]. For indirect modulation, the feedback also allows
multiple round trips through the modulation element [168,169]. If the modulation frequency is very close to the longitudinal mode spacing of the laser (which is determined by the total length including the external cavity) then the system should operate as a mode-locked laser [176]. Active mode-locking by frequency modulation of diode lasers with optical feedback has been demonstrated by several authors [225-229]. If the modulation frequency is detuned by a small amount from the cavity mode spacing then the system operates as an FM laser but the modulation index is significantly enhanced by the external cavity mode frequency. This enhancement of the modulation index is accompanied by the induction of a coherence collapsed state when the modulation power is increased [168,169]. Dynamic instabilities observed in frequency modulated diode lasers with optical feedback [230-235] prevent wide bandwidth output, which is desirable for many applications [236].

2.6. Summary

A unique characteristic of diode lasers is that they are very susceptible to dynamic instabilities. A number of factors, such as the strong coupling of the refractive index to the carrier density inside the laser active layer, which leads to the linewidth enhancement factor and strong relaxation oscillations (which drive many of the instabilities), and the relatively low facet reflectivities, are responsible for this. As discussed in this chapter the instabilities can be induced by optical (and phase conjugate) feedback, optical injection, and frequency modulation. Differences between the phase correlation, the frequency detuning, and the spatial mode matching of the diode laser output field to the feedback or injected field lead to substantially different dynamic behaviour. The principal mechanism responsible for causing instabilities in each case is the coupling of the phase of the electric field inside the laser cavity to the carrier density and photon number. This can result in fluctuations of the output power and an increase in the number of lasing modes.

While diode lasers are susceptible to instabilities induced by feedback and injection these can also be used to improve many of the operating characteristics. As discussed in this chapter the diode laser output side-mode-suppression, the linewidth, the threshold injection current, and the intensity and frequency noise can all be reduced by feedback or injection. Frequency tunability and stability can also be enhanced. These occur for specific levels of feedback and detuning. These factors make the output of diode lasers more appropriate for many applications.
Chapter Three: Misaligned Optical Feedback

3.1. Introduction

Diode lasers subject to optical feedback have found application in a number of areas, as discussed in section 2.2. The majority of applications employ strong feedback (regime V) due to the benefits of increased frequency stability, increased side mode suppression, narrowed linewidth, and reduced threshold injection current [24-26]. It is important in such a system to understand the relative effects of the many system variables that can influence the system output. One particular variable that is known to influence many of the system output characteristics, such as the power, the optical spectrum, and the noise, is the alignment of the optical feedback field with respect to the diode laser cavity [237,238]. Changing the orientation of the external mirror or grating (introducing asymmetric optical feedback), changes both the level of feedback into the diode laser, and the spatial mode coupling between the output transverse mode and the feedback mode. It is important to fully understand the relationship between the orientation of the external mirror and the spectral and steady state characteristics of the system, in order to determine the correct alignment and the procedure with which to achieve this, for a given application.

Limited research has previously been reported on the effects of misaligned (asymmetric) optical feedback. The power dependence on the external mirror tilt has been studied for Hitachi HLP 1400 diode lasers at injection currents close to the solitary diode laser threshold [237-239]. Undulations in output power with increasing external mirror tilt were observed and attributed to a combination of changes in coupling efficiency, phase interference and multiple round trip diffraction. This is shown in figure 3.1, below. In addition, the misaligned feedback was found to effect the output spatial mode of the laser; higher order transverse modes were observed for large mirror tilts. Variations in spectral output with mirror alignment have also been observed, and are shown in figure 3.2. A transition to multi-mode operation was reported for certain asymmetric alignments of the external mirror. Similar undulations, and transitions to regions of different dynamic stability (including LFF), with external mirror tilt have also been reported [73,240] (also for HLP 1400 diode lasers).
Figure 3.1. Variations in output power with external mirror tilt in the vertical direction for various injection currents. The inserts show far-field interference patterns at the indicated tilt angles and currents. The diode laser threshold current is 42 mA. After [238].

In the present work, the behaviour of diode lasers subject to strong optical feedback from a plane mirror has been investigated. In particular, the output power and the optical frequency spectrum of the diode laser, as a function of a systematic variation of the axial alignment of the external mirror, has been examined. It is found that at higher injection currents the maximum output power can occur for a non-axial (asymmetric) alignment of the external mirror. This result can be explained by variations in slope efficiency and threshold injection current when a systematically varying effective reflectance is taken into account. The formalism for calculating these is relatively well understood [26,184], but has not been applied to variations in axial alignment previously. Comparison of experimental results with calculations shows good qualitative agreement. Additionally, it is found that the optical frequency spectrum of the diode laser output varies systematically with external mirror alignment and shows dynamic instabilities. Two diode lasers from different manufacturers (STC and SDL) have been used in the system, and are shown to have different systematics with respect to the spectral content and intensity noise with varying external mirror alignment. The results with one laser (STC) are consistent with the current understanding of semiconductor lasers with varying levels of optical feedback. The second laser (SDL) is also consistent with this but additionally shows that single-frequency operation is limited to lower injection currents when optical feedback is present. This result suggests that spatial hole-burning leads to multi-mode operation at modest injection currents when strong optical feedback is present in this device. These results have significant implications for the practical
methods utilised when optimising the alignment of such systems, and the output power that can be achieved with little susceptibility to the onset of dynamic instability with technical noise perturbations. The two different laser diodes used are both quantum-well, index-guided devices that are commonly employed in a number of practical systems.

The diode lasers used in the current study are of similar construction to those used in the earlier studies, ie quantum-well, index guided ~800 nm devices. The other studies considered only low feedback ($R_{\text{ext}} < 0.10$), solitary diode laser injection currents close to threshold ($I/I_{\text{th}}^{dl} < 1.2$), and a diode laser with a relatively long coherence length (50-100 cm). A wider range of parameters is used in the current study. Effects have been examined with higher injection currents ($I/I_{\text{th}}^{dl} < 3$), with higher feedback fractions ($R_{\text{ext}} > 0.9$), and for a range of external cavity lengths including shorter values (from 75 mm to 300 mm). The system studied is insensitive to the phase of the feedback because the cavity length exceeds the spatial coherence length of the laser diode combined with collimating optic. No multiple round trip diffraction effects are observed in the current work. The reliance on these different parameters leads to different physical mechanisms which leads to substantially different results. A single relative maxima or minima for symmetric alignments, which spans a large range of tilt angles is observed, as opposed to undulations at very small tilt angles. Different spectral transitions are also observed, as discussed in section 3.5.

![Figure 3.2. Variations in the output optical spectra for various tilt angles (external cavity length $L = 50$ cm, injection current $I = 1.3 I_{\text{th}}^{dl}$. The tilt angles are (a) 12 $\mu$rad, (b) 24 $\mu$rad, (c) 36 $\mu$rad, (d) 48 $\mu$rad, (e) 60$\mu$rad, and (f) 72 $\mu$rad. After [238].](image)
3.2. Experiment

3.2.1. Set-up

The experimental set-up is shown in figure 3.3. It consists of a diode laser mounted on a heat sink and temperature controller, a collimating optic (Melles Griot GRIN rod lens #06LGT214) on a piezoelectric translation stage, and an external plane mirror ($R_{mirror} = 0.90$) mounted on a piezoelectric mirror mount with vertical and horizontal rotation adjustments (~ 1 degree/ rev for a 300 mm cavity). An uncoated intracavity beamsplitter (10 mm thickness) is used to monitor the system output, and an intracavity neutral density attenuator is used to control the amount of feedback. The output power is monitored with an Ophir (Nova Display) power meter. The optical spectrum is recorded with a 8 or 1000 GHz FSR Fabry-Perot interferometer, the output beam profiles are recorded with a Spiricon Laser Beam Analyser and CCD camera, and the output wavelength is observed on a Burleigh wavemeter (# WA-10). The laser device is either a 50 mW SDL (model #5400C) 848 nm cw diode, or a 50 mW STC (model #LT50-03U) 850 nm diode. The free-running threshold injection current is approximately 32 mA for the STC device, and 18 mA for the SDL device (see appendix A for a full list of diode laser parameters). In order to avoid spurious reflections from diagnostics entering the diode laser via the intracavity beamsplitter, optical isolators (providing >30 dBm isolation) are used between any external optical surface and output 1 or output 2. These are used throughout this thesis for all experiments.

Figure 3.3. Experimental arrangement.
3.2.2. Coupling efficiency

Crucial to any theoretical model describing feedback behaviour is the amount of feedback that is actually coupled into the diode laser. This is important for comparisons between experimental data and theory, and comparisons between different experimental systems. The coupling efficiency, $\eta_c$, represents the efficiency by which the external feedback field is coupled into the diode laser gain region. The external feedback fraction, $R_{\text{ext}}$, representing the ratio of the feedback power in front of the collimating optic to the output power (also in front of the collimating optic), is defined, in terms of the experimentally observable quantities, by

$$R_{\text{ext}} = \left(1 - R_{\text{bs}}\right)^n \frac{P_{\text{out}2}}{P_{\text{out}1}},$$

(3.1)

where $R_{\text{bs}}$ is the reflectivity of the beamsplitter facet(s), and $P_{\text{out}1}$ and $P_{\text{out}2}$ are the output powers measured at output 1 (from reflection off the front beamsplitter facet) and output 2 (from reflection off the back beamsplitter facet) respectively. For a beamsplitting substrate, used in this work, $n=2$, representing loss due to reflection off both beamsplitter facets. For a beamsplitting cube, $n=1$, as there is only one facet. This definition for $R_{\text{ext}}$ is used throughout this thesis.

Various methods have been proposed and used to estimate $\eta_c$ for a given system [en,bh,xr]. Such methods usually consider the changes in slope efficiency and threshold injection current induced by a range of feedback levels. Values predicted in the literature of the coupling efficiency for a diode laser with conventional optical feedback range from 0.02 to 0.7 [43,241]. The exact value is dependent on the specific system parameters such as the collimating optic, the external cavity length, and the size, wavelength, structure, and facet reflectivities of the solitary diode.

The coupling efficiency can be estimated from fits of experimental data for variations in slope efficiency and threshold injection current with external feedback fraction, to theory predicted by equations (2.24) and (2.25). No explicit solution is possible because there are only two equations and three unknown parameters (the coupling efficiency, $\eta_c$, the internal quantum efficiency of the solitary diode laser, $\eta_{\text{int}}$, and the internal loss factor of the diode laser, $\alpha_{\text{int}}$). Some approximation is therefore required.

The method used here is to fit the experimental data for changing slope efficiency and threshold injection current with the theory using an initial estimation of $\eta_{\text{int}}$. Various independent determinations give values of the internal quantum efficiency for diode lasers
that depend on the type and fabrication of the diode, but are generally above 0.5 [242]. The value for a quantum-well diode laser is generally assumed to be much higher than other device types. Therefore, $\eta_{int}$ is initially given a value in the range 0.6-1.0. $\alpha$ and $\eta_c$ are then varied until the best fit to the experimental data is found for both equations. This is repeated for a number of values of $\eta_c$ (over the whole range 0.6-1.0). It is found that a range of $\eta_c$ and $\alpha_{int}$ give reasonable agreement to the experimental data points for a range of $\eta_{int}$. This determines the parameters and their uncertainties. Parameters used in the model are given in appendix A.

The experimental data and theoretical fits are shown in figure 3.4 for the STC diode. The unknown parameters are determined to be: $\eta_c = 0.28 \pm 0.07$, for $\eta_{int} = 0.85 \pm 0.10$, and $\alpha_{int} = (2900 \pm 800)$ cm$^{-1}$. Similar fits have been accomplished for the SDL diode laser. The parameters are: $\eta_c = 0.18 \pm 0.06$, for $\eta_{int} = 0.70 \pm 0.15$, and $\alpha_{int} = (2300 \pm 700)$ cm$^{-1}$. The method has been used for several STC laser diodes and several SDL laser diodes. Comparable values for each device of each type of laser diode are obtained, ie the SDL diode laser typically has much lower coupling of the external feedback field into the diode laser waveguide. These values are in agreement with typical values given in the literature for diode lasers such as HLP1400 ($\eta_c \sim 0.36$) [208,238,241].

Figure 3.4. Slope efficiency and threshold injection current as a function of the external feedback fraction for the STC diode laser with feedback. The solid lines represent fits to the experimental data points (triangles) from equations 2.24 (a) and 2.25 (b).
3.3. Alignment current

In a diode laser with feedback system, the external mirror is typically aligned, relative to the optical axis of the diode laser output, to achieve the maximum output power. It is found, however, that the injection current of the diode laser at which this alignment procedure is performed (the alignment current), influences both the output power versus current characteristics (through the threshold injection current and slope efficiency) and the output optical frequency spectrum.

![Figure 3.5](image-url)

*Figure 3.5. Output power versus injection current curves for three cases: no feedback, alignment of the external mirror at high current, and alignment at low current.*

The output power versus injection current curves for an SDL diode laser aligned (for maximum power) at a high injection current and at a low injection current are shown compared with the diode laser output with no feedback in figure 3.5. The presence of the feedback is shown to reduce the threshold current and slope efficiency relative to the solitary diode laser, as expected from theory (section 2.2.2). However, the two different alignments result in two distinct power versus injection current curves. Such behaviour has been recorded previously for shorter external cavities [135], but attributed to changes in the phase of the feedback with mirror translation. In this study the slope efficiency and threshold current are independent of the phase of the feedback as the cavity length (~300 mm) exceeds the spatial coherence length (< 75 mm) for the laser diode combined with the collimating optic [241].

The correspondence of external mirror alignment to the resulting power versus injection current curve is further quantified by examining the variations in threshold injection current...
and slope efficiency for the external mirror aligned at different injection currents (representing different orientations). This is shown in figure 3.6. The lowest threshold injection current and slope efficiency represents symmetric feedback (on optical axis), as this corresponds to the maximum coupling between the external feedback field and the diode laser internal cavity. This is shown to occur when the output power is maximised for external mirror alignment at a low diode injection current (below the solitary diode threshold). Increasing the injection current at which the external mirror is aligned (again for maximum power) has the effect of increasing the operating threshold and slope efficiency towards that of the solitary diode. For injection currents above $3I_{th}^{dl}$ the system cannot be aligned (for maximum output power) as there is no increase in output power with feedback, ie the slope efficiency and threshold current are both above that of the solitary diode laser. Thus at higher injection currents the presence of feedback, indicating an injection of photons, actually reduces the charge carriers being produced within the diode laser active layer. This is an intuitively unexpected result.

Figure 3.6. Change in slope efficiency (a), and threshold current (b), as a function of the current at which the system is optimised for maximum power (alignment current). The dotted line represents the solitary diode lasers’ slope efficiency and threshold injection current in (a) and (b) respectively.

The alignment current is also found to effect the resulting output optical frequency spectrum. Figure 3.7 compares the range of injection currents that result in stable single-mode operation as a function of the alignment current for the two different types of laser diode. The shaded regions represent stable single-mode operation and the unshaded regions represent
multi-mode output. If the STC diode laser (figure 3.7 (a)) is aligned at a low injection current (i.e., on-axis symmetric feedback) then stable single-frequency operation is obtained for the full range of the diode laser’s operating current (20-50 mA). Alignment at higher currents, however, results in only a small range of injection currents giving stable single-mode output. Conversely, the SDL laser diode operates single-mode for the largest injection current range when the external mirror is aligned at injection currents above $I_{th}^{dl}$ (representing off-axis alignment). Single-mode operation is not obtained for alignments close to symmetric.

![Figure 3.7](image.png)

**Figure 3.7. State of the output optical frequency spectrum as a function of injection current and alignment current. Solitary diode laser in (a) is STC, and in (b) is SDL.**

Figures 3.5 and 3.6 represent the initial observation that an intricate relationship exists between the alignment of the external mirror, the injection current of the solitary diode, and the output power (determined by the relationship between the slope efficiency and threshold injection current), and that for certain ranges of parameters a reduction in the output power is observed with feedback. Figure 3.7 represents the initial observation that there is also an intricate relationship between the alignment of the external mirror and the frequency mode structure (or stability) of the output, which is also related to the output power through the alignment procedure used, and is dependent on the solitary diode laser. The remainder of this chapter is dedicated to providing a more complete understanding of the features displayed in these figures.
3.4. Output power versus external mirror alignment

3.4.1. Model

A model is described that characterises the change in output power as a function of the external mirror tilt about any axis and the diode laser injection current. The external cavity diode laser system can be considered equivalent to a solitary diode by replacing the front facet reflectivity of the laser diode, $R_2$, coupled to an external plane mirror with reflectivity $R_{\text{mirror}}$ (generating an external feedback fraction of $R_{\text{ext}}$), with an effective reflectivity, $R_{\text{eff}}$, as described in section 2.2.2 (equations 2.20-2.23). Equation 2.23 is valid provided that the feedback field is on the optical axis of the system.

To model the effect of a systematic misalignment of the external mirror, a spatial dependence is added to the coupling coefficient, $\eta_c$. This dependence is chosen to be a simple Gaussian function of the angle of the external mirror, $\theta$, with respect to the optical axis in a plane transverse to the diode laser stripe

$$
\eta_c(\theta_{v,h}) = A_{v,h} \exp\left(-\frac{2\theta_{v,h}^2}{w^2}\right).
$$

(3.2)
The coefficients $A_v$, $A_h$, and $w$ are determined from fits of the horizontal and vertical beam profile normalised to the maximum coupling coefficient, and the angular displacement of the feedback beam (experimentally determined). This is shown in figure 3.8, above. These variables have the values $A_v = 0.061$, $A_h = 0.091$, and $w = 0.265$, for the STC laser diode (shown in figure) and $A_v = 0.058$, $A_h = 0.095$, and $w = 0.0288$ for the SDL laser diode.

The Gaussian functionality of the coupling efficiency represents the convolution of the Gaussian feedback field with the fundamental transverse (Gaussian) mode of the laser diode output. Experimental observation of the output beam profile as a function of the alignment of the feedback field shows that the entire feedback field is coupled into this fundamental transverse mode of the diode laser.

![Figure 3.9](image)

*Figure 3.9. Output beam profile in plane perpendicular to the laser diode stripe for a range of alignments of the external mirror in the same plane (horizontal). (a) represents symmetric on-axis feedback. Other curves show mirror misalignment of (b) +0.1°, (c) -0.1°, (d) +0.2°, (e) -0.2°,(f) +0.3°, (g) -0.3°, and (h) +0.5° no feedback, (i) -0.5° no feedback.*

Figure 3.9 shows the horizontal output beam profile for a range of misalignment angles (both positive and negative) of the feedback field in the horizontal plane. If any of the feedback field was coupled into a higher order mode then this would manifest itself as an asymmetry in the beam profile with respect that of the diode laser with no feedback, or an asymmetry with respect to positive or negative external mirror tilt. No such asymmetry is observed. Therefore, the feedback is always coupled into the same spatial mode within the semiconductor cavity, and is subject to the same gain region within the semiconductor active region regardless of the external alignment.
The spatial dependence of the coupling coefficient introduces a spatial dependence to the external reflectivity coefficient, \( r_3 \)

\[
r_3(\theta_{v,h}) = \sqrt{\left(\eta_c(\theta_{v,h}) R_{\text{ext}}\right)}(1 - 0.002I),
\]

and thus to the effective reflectivity

\[
R_2'(\theta_{v,h}) = (R_{\text{eff}})_{\text{max}} = \frac{r_2 + r_3(\theta_{v,h})}{1 + r_2 r_3(\theta_{v,h})}^2.
\]

The factor \((1-0.002I)\) in equation (3.3) corrects for additional loss due to beam expansion in the practical system as the current is increased. It is needed to maintain quantitative agreement between experiment and theory as injection current is increased and it is common to the system using both laser diodes, and therefore not relevant to explaining the difference in the spectral characteristics of the system with these two devices.

The reduced slope efficiency, in watts per amp, for the equivalent laser device, providing \( r_1 = 1 \), is given by

\[
\eta_{\text{ext}}\eta(\theta_{v,h}) = \frac{\ln\left(\frac{1}{R_2(\theta_{v,h})}\right)}{2\alpha_{\text{int}} L + \ln\left(\frac{1}{R_2(\theta_{v,h})}\right)} \eta_{\text{int}}\left(\frac{hf}{e}\right)(1 - R_{bs})
\]

where the factor \((1- R_{bs})\) accounts for coupling the intra-cavity power through the external mirror or beamsplitter. The reduced threshold injection current due to the presence of optical feedback is given by

\[
I_{\text{th}}_{\text{ex}}(\theta_{v,h}) = I_{\text{th}}^{dl} \left(1 + 2 f_d \tau_p \ln\left(\frac{1 + r_2 r_3(\theta_{v,h})}{r_2 + r_3(\theta_{v,h})}\right)\right).
\]

The output power, \( P \), as a function of external tilt angle, \( \theta \), and injection current, \( I \), can then be expressed by

\[
P(\theta_{v,h}, I) = \eta_{\text{ext}}(\theta_{v,h}) \left[I - I_{\text{th}}_{\text{ex}}(\theta_{v,h})\right].
\]

The output power determined by equation 3.7 is shown in figure 3.10, as a function of horizontal external mirror tilt and solitary diode laser injection current. For low injection currents (close to \( I_{\text{th}}^{dl} \)), the maximum power occurs for symmetric on-axis feedback. At such currents the change in power with feedback is large (compared with the solitary diode laser output power) and is always positive (ie the feedback always causes an increase in feedback power). This behaviour is expected from accepted diode laser with feedback theory, and has previously been observed [243].
3.4. Output power versus external mirror alignment

Figure 3.10. Theoretical prediction of output power versus injection current and horizontal misalignment of external mirror from equation 3.7. Zero mirror tilt represents on-axis symmetric optical feedback.

As the injection current is increased (~ $2I_{th}^{dl}$) the output power for symmetric alignments reduces relative to the diode laser power with no feedback, and the maximum power is found for off-axis alignments (± 0.2-0.4 °). For high injection currents (> $3I_{th}^{dl}$) the output power of the system with feedback is always less than the power of the solitary diode laser, and is minimum for on-axis alignments. The maximum effect of the feedback is a small (always negative) change (< 10%) on the system output power. This reduction in output power with feedback at high injection currents, which has not previously been reported, agrees with the initial observations made in section 3.3 (figures 3.5 and 3.6). It occurs due to the relative increase in both threshold injection current and slope efficiency in the presence of feedback.

In figure 3.11 the output power is shown as a function of the external mirror tilt for any orientation (horizontal versus vertical) for a number of different injection currents. As expected simply from the geometry of the laser diode (ie the active layer is a horizontal stripe), misalignment in the vertical direction results in similar behaviours but over a smaller range of angular displacement.
Figure 3.11. Theoretical prediction (equation 3.7) of output power as a function of external mirror alignment (horizontal versus vertical tilt) for a number of values of injection current ($\frac{I}{I_{th}}$): (a) 0.8, (b) 1.3, (c) 1.8, (d) 2.3, (e) 2.8, (f) 3.3, for the SDL laser diode parameters.
3.4. Output power versus external mirror alignment

The exact relationship of output power to mirror tilt and injection current is strongly influenced by the three parameters: $\eta_c$, $\eta_{int}$, and $\alpha_{int}$, which have significant uncertainties. The data in figures 3.10 and 3.11 is for the STC diode laser parameters. Changing these values within their uncertainties does not change the general form of the relationship, but changes the magnitude of observed trends, ie the difference between the highest and lowest powers induced by the feedback. Similar results are also obtained with the SDL diode laser parameters.

3.4.2. Comparison with experimental results

The output power versus external mirror alignment has been examined for four different types of diode laser. Two laser diodes have been the subject of an extensive and systematic examination (the SDL and STC devices) and preliminary investigations have been done with both HLP1400 and APL devices. For all devices, agreement is found with the general trends predicted by the model. At injection currents close to threshold, the output power is maximum for symmetric alignments, decreasing with external mirror tilt about any one axis. For high injection currents a minimum power, which is below the solitary diode output power with no feedback, is found for symmetric alignments. This indicates that this is typical behaviour for most narrow-waveguide diode lasers with strong feedback. In addition, although a diode laser with optical feedback from an external grating has yet to be the subject of a systematic study, similar variations of output power with alignment have been observed with such systems.

When either of the STC or SDL diode lasers are operated with feedback in a short external cavity at injection currents close to the solitary diode laser threshold, then symmetric feedback results in the maximum output power, and misalignment of the external mirror about any axis causes undulations in the output power. This is similar to the behaviour observed by Seo et al [238] (depicted in figure 3.1), for similar experimental parameters but with different diode lasers. This indicates that as the external cavity length and injection current are reduced different mechanisms (phase interference and multiple round trip diffraction) are responsible for the diode laser output power. This is not applicable to the current model.

Experimental data for the variation of output power with horizontal external-mirror tilt is shown in figure 3.12 (graphs a-f) for a number of injection currents. The experimental parameters are applicable to the model described in the previous section. The solitary diode laser is an SDL device and the external cavity is 300 mm. In each case, the external mirror
was first aligned at low current in order to produce symmetric feedback, and then the current increased before tilting the external mirror through approximately one degree in a number of steps. At all currents the output power is found to vary in a systematic way as the external mirror is tilted about any one axis. This is compared to the theoretical prediction, with the SDL parameter values, in the figure (graphs g-l). Good qualitative agreement is shown. Comparison between the experimental data and the theoretical prediction for the STC diode laser with vertical external-mirror tilt, in figure 3.13, also shows good qualitative agreement.

Although there is good qualitative agreement for each laser diode (between theory and experiment) in terms of the general trend of the power fluctuations with mirror tilt, there is some quantitative disagreement. Although the theory does predict the comparative power at

**Figure 3.12.** Output power as a function of the horizontal tilt of the external mirror for a range of different diode injection currents: 15 mA (graphs a and g), 29 mA (b and h), 37 mA (c and i), 43 mA (d and j), 49 mA (e and k), and 55 mA (f and l). Graphs a-f are experimental data, g-l are the (one-dimensional) theoretical prediction. The solitary diode laser is SDL, $I_{th}^{dl} = 18$ mA.
each alignment, the exact value of the output power and the magnitude of the differences in power between mirror alignments at a given injection current does not agree. For this reason, the output power in each theoretical plot has been normalised to the experimental value. This quantitative discrepancy arises principally from the uncertainty in the unknown parameters; there is a change in the output power level with small changes in these parameters, but they do not significantly effect the qualitative trends.

Figure 3.13. Output power as a function of vertical mirror tilt for the STC diode laser ($I_{th}^{dl}=32$ mA). Graphs a,b,c are experimental data, d,e,f theoretical prediction. Injection current is 30 mA in (a, d), 48 mA in (b, e), and 65 mA in (c, f).
3.5. Output spectrum versus external mirror alignment

The relationship between the external mirror alignment and the resulting optical frequency spectral output of the system has been examined and compared for the two types of laser diode; both show distinct characteristics. The optical frequency spectrum is found to evolve through a series of different states, representing different dynamic conditions, as the external mirror is tilted about any one axis. In figure 3.14, the evolution of the optical frequency spectrum at resolutions of both the solitary diode mode frequency (~87 GHz for the STC diode laser, ~112 GHz for the SDL diode laser) and the external cavity frequency (500 MHz for a 300 mm external cavity) is shown for an increasing external mirror tilt (in the horizontal plane) from symmetric alignment (spectra a,g,m,s).

Figure 3.14. Optical frequency spectra at a number of tilt angles of the external mirror for the STC diode laser (two left columns) and the SDL diode laser (two right columns). The horizontal tilt angles are indicated at left of figure. The injection current is approximately $1.4 I_{th}^{dl}$ for both diode lasers.
This sequence of evolution of the output frequency spectrum (fig 3.14 a-f, and g-l) for the STC diode laser with increasing misalignment is to be expected from accepted optical feedback theory. The STC diode laser operated with symmetric on-axis feedback results in stable single-mode output, with good side mode suppression (> -30dBm), for the full range of the diode laser’s operating current (spectra (a,g)). This represents alignment at a low current (cf figure 3.7) and the maximum feedback coupled into the diode laser (ie well within regime V). As the external mirror tilt is increased a range of alignments near symmetry result in stable single-mode behaviour (fig 3.14 (b,c) and (h,i)). If the external mirror is further tilted, however, a transition is observed to a multmode state that is characteristic of coherence collapse (regime IV behaviour). Characteristics of the coherence collapsed state are a number of modes lasing on the solitary diode laser frequency (d,e) and a deep modulation of the modes of the external cavity (j,k). Further tilting of mirror results in the nearly single-mode output of the diode laser with no feedback (f) and (l). Side-modes (not resolved in the figure), occur at suppression ratios of approximately –20 dB. Regime III, II or I behaviour is not observed by tilting the mirror because these regimes occur at very low levels of feedback and at the large tilt angles where they would be expected the coupling efficiency is decreasing with the largest gradient. In addition, the front facets of both diode lasers are anti-reflection coated; this increases the relative feedback ratio, making it harder to enter the lower feedback regimes.

The SDL diode laser subject to misaligned feedback shows somewhat different behaviour. For symmetric feedback, and alignments close to this, the SDL diode laser operates in a multi-mode state for \( I > 1.2 I_{th}^{dl} \) (spectra (m,n) and (s,t)). As the external mirror tilt is increased only a small range of tilt angles results in stable single-mode operation, (o) and (u), before there is another transition into multi-mode behaviour, (p,q) and (v,w). Finally, the nearly single-mode output of the diode laser with no feedback is observed (r, x).

As was the case for output power variations with external mirror tilt, preliminary investigations have been carried out with other diode lasers on the effects of external mirror tilt on the output optical frequency spectrum. It is found that HLP1400 diode lasers behave similarly to SDL diode lasers; ie they operate multi-mode for symmetric alignments at high currents.

The multi-mode optical frequency spectra observed at large tilt angles shows the same characteristics for all the laser diodes studied as the STC diode laser system. These characteristics include an increase in the number of modes of the solitary diode laser ((d,e) and (p,q)), and a deep modulation of the external cavity mode frequencies ((j,k) and (v,w)),

3.5. Output spectrum versus alignment

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indicating that this is also regime IV, behaviour. The multi-mode spectra observed at and around the symmetric alignment, for the SDL laser, are distinct from this. A deep modulation at the solitary diode laser mode frequency, and an absence of mode structure at the external cavity mode frequency, is observed. This deep modulation at the solitary diode laser mode frequency \((m,n)\) is similar to the modulation of the external cavity mode frequency observed for regime IV operation at the higher resolution \((v,w)\). This indicates that the multi-mode state for symmetric alignments is a distinct state, which probably comprises much larger frequencies than the solitary diode laser mode frequencies, as the deep modulation of the external cavity modes in regime IV indicates the presence of a higher frequency component (that of the solitary diode mode frequencies). Such unstable multi-mode operation has been observed previously, but the distinction between the two types of instability has not been identified.

A comparison of the evolution of the state of the output frequency spectrum with injection current, as a function of vertical and horizontal external mirror tilt, is shown in figure 3.15. The grey regions represent alignments (vertical versus horizontal mirror tilt) which give stable single-mode operation, and the unshaded regions represent coherence collapsed/multi-mode output. The lightly shaded areas, at large tilt angles, refer to the solitary diode operating with no feedback. At injection currents below the solitary diode laser threshold \((a \text{ and } e)\) most alignments give stable single-mode operation for both diode lasers. If the injection current is above the solitary diode threshold, the region of coherence collapsed output is increased for both diode lasers \((b \text{ and } f)\), and the SDL diode laser exhibits multi-mode operation for alignments close to symmetric. This multi-mode state occurs when the output power versus external mirror tilt begins to plateau. As the injection current is increased further \((c \text{ and } g)\) the range of alignments giving regime IV coherence collapsed output increases for both laser diodes, and the area around the symmetric alignment giving unstable output increases for the SDL laser diode (ie alignments for which there is a decrease in the output power with feedback relative to the maximum output power). At higher injection currents \(>2.5 I_{th}^{dl}\) there is no alignment which results in stable single-mode output for the SDL diode laser \((h)\), and there is always a region of alignments close to symmetric that result in stable single-mode operation for the STC diode \((d)\).
Figure 3.15. Output stability as a function of external mirror alignment (horizontal versus vertical mirror tilt) and output power. The Grey regions (sm) represent stable single-mode operation, the unshaded regions (mm) represent multi-mode operation, and the light grey area (nf) is the solitary diode laser with no feedback. Plots a,b,c,d are for STC diode laser; e,f,g,h are for SDL diode laser. Injection currents are $0.8I_{th}^d$ (a and e), $1.1I_{th}^d$ (b and f), $2I_{th}^d$ (c and g), and $2.6I_{th}^d$ (d and h).
In each of the above experiments, a number of both STC and SDL diode lasers (at several wavelengths) have been tested. It is found that all the SDL diode lasers exhibit a transition (with increasing current) to multi-mode behaviour for symmetric alignments, and all the STC diode lasers are single-mode at these alignments (and all currents). The current at which the transition to multi-mode behaviour for axial alignment occurs for SDL diode lasers is dependent on the external reflectivity and the diode temperature. This dependence is shown in figure 3.16, below. As the external feedback fraction is decreased (b) the transition is observed to occur at higher currents. The graph shows an approximately linear inverse proportionality; the exact relationship is not determinable from the experimental data. This indicates that the transition may also occur in the free-running diode laser with no feedback for very high currents, which are above the specified maximum operating current for the diode laser and therefore not observed. As the temperature of the laser is increased (a) the transition is found to occur at lower currents; this is indicative of increased nonlinear gain saturation caused by carrier heating.

Any diode laser is expected to operate multi-mode at high injection currents due to spatial hole-burning (caused by longitudinal spatial variation in the gain) or spectral hole-burning (caused by nonlinear gain saturation) [22]. Dynamic instabilities caused by these mechanisms are similar to the dynamic instabilities caused by optical feedback in diode lasers [244]. The effect of introducing feedback into the SDL diode may be to dramatically increase the laser’s susceptibility to either of the above effects (such that they occur at relatively low
The SDL and STC diode lasers show a clear difference in sensitivity to such nonlinear hole-burning effects with and without feedback.

Increase in longitudinal spatial variation in the gain with optical injection in the SDL device is similar to that predicted for semiconductor optical amplifiers [177]. Theoretical work on semiconductor optical amplifiers predicts that devices with lower resistivity and higher asymmetry in the reflectance of the device facets will result in large longitudinal spatial hole-burning effects [245]. The exact reflectance of the facets of the laser diodes used is proprietary information but it is known that they are both high reflectance (~95%) / low reflectance (~5%) devices, i.e., highly asymmetric. The resistivity of the SDL laser is marginally lower than that for the STC laser. An alternative view of longitudinal spatial hole-burning, based on the self-induced grating of the standing wave, predicts multi-mode operation will be induced by increased spatial hole-burning with increasing injection current when an index grating and/or a gain grating is formed [177]. Devices with rapid spatial diffusion of the gain can reduce the self-induced grating [22] and thus prevent multi-mode operation due to spatial hole-burning, on this wavelength of light scale.

Further theoretical work needs to be undertaken to determine whether either of these mechanisms, or others, for spatial hole-burning shows an increase in the effect with optical feedback as is observed in the experiments being reported for the SDL laser, and whether spectral or spatial hole-burning is the dominant mechanism. Two descriptions of spatial hole-burning that have appeared in the literature [177, 245] suggest appropriate approaches to the theoretical modelling of these systems. Such knowledge will lead to new capabilities in designing, or choosing, a diode for use in a strong feedback diode laser system whose spectral content will be less sensitive to misalignment or fluctuations in injection current, and will remain single-mode for higher output powers.

Another effect of altering the external mirror alignment on the output optical frequency spectrum is to induce mode hopping of the output between the longitudinal modes of the solitary diode. Figure 3.17 (a) shows the optical spectrum as recorded on a 1000 GHz FSR interferometer as the external mirror is tilted from the on-axis alignment by approximately 0.1 degrees. The data is for the STC diode laser at an injection current of approximately $1.2 I_{th}^{dl}$, at this injection current the output is stable for most alignments. The mode hopping is observed at higher currents within the stable single-mode operating regions. The output optical frequency increases in steps that are approximately equal to the longitudinal mode spacing of the diode laser (87 GHz). Figure 3.17 (b) shows the output wavelength as the external mirror is scanned through approximately 0.6 degrees. The wavelength separation
between the solitary laser diode modes is 0.21 nm, which is close to the average separation of the points. Figure 3.17 (c) shows the output wavelength as a function of injection current for the diode laser with no feedback. This demonstrates the magnitude of the wavelength shift is similar for an increase in injection current and for an increase in optical feedback.

![Figure 3.17](image_url)

**Figure 3.17.** (a) Series of optical frequency spectra (shifted vertically for clarity) as the external mirror is tilted through ~0.1 degrees. (b) Output wavelength versus external mirror tilt angle for the STC diode laser at 40 mA and $R_{ext} = 0.95$. (c) Output wavelength versus injection current for the solitary diode laser (no feedback).

The observed mode hopping can be explained by considering that as the mirror is misaligned, the power injected into the diode laser cavity decreases, hence the carrier density within the semiconductor decreases. This increases the refractive index and hence the emission frequency. The continuous shift in the wavelength causes the mode that was originally dominant to move away from the gain peak. The system then lases on the next dominant mode, which is the adjacent longitudinal mode of the solitary diode laser (as these
modes are dominant over the external cavity modes). This mode is shifted towards the gain peak, resulting in mode hopping. This is similar to the mechanisms by which the output wavelength is influenced by the injection current. Additionally, the external cavity length and feedback phase are both changed when the mirror is rotated; this is known to cause mode hopping [246].

3.6. Summary

The results described in this chapter represent the first systematic investigation of the effects of the external mirror alignment on the operating characteristics of a diode laser with feedback from a plane mirror. Two different diode lasers have been contrasted in the system. A theory predicting output power variations with misaligned feedback, based on the reduction of the slope efficiency and threshold current as a function of a spatially dependent coupling coefficient, gives close qualitative agreement with the experimental observations for the two diode lasers examined in detail. Several other types of diode laser also display the general characteristics predicted by the model.

The two different diode lasers display different spectral output dependency on external mirror tilt. Of the diode lasers examined, the STC device is clearly more suitable for most applications that require single-frequency output at the highest possible power. The SDL laser is less suitable for use in a feedback system where the feedback is axial or close to axial as there are only a small range of useable injection currents which result in single-mode output. In particular, the SDL diode laser is inappropriate for a system that uses phase conjugate feedback as the conjugate reflection will always be symmetric on-axis. Similarly, feedback from a short external cavity will be much closer to axial alignment than for a long external cavity. Such feedback configurations are discussed in more detail in later chapters. Several other diode laser types are found to behave similarly to the SDL diode laser.

The reason for the preferred behaviour of the STC diode laser is not clear. Both lasers are of similar construction, ie, quantum-well devices with similar cavity lengths, and similar dielectric facet coatings. Possible differences between the lasers that may lead to the distinct characteristics observed include the relaxation oscillation damping, the linewidth enhancement factor, and other internal laser parameters. Further study is needed to ascertain the relative importance of these variables.
4.1. Introduction

A large number of parameters contribute to the output state (stability and power) of a diode laser with optical feedback. It is important to understand what range of parameters will give the most appropriate output for a given application. Important variables of a feedback system describe the type of diode laser (length, facet coatings, and internal parameters), its operating parameters (injection current) and the characteristics of the feedback field (feedback power, external cavity length, and feedback phase). Of particular significance for a number of short cavity applications (such as integrated feedback and frequency modulated devices) is how the coherence state of the diode is influenced by the length of the external cavity. Additionally, the robustness of a given system against mechanical vibrations can be ascertained by examining how its output state varies with feedback phase.

Based on a numerical analysis of the Lang-Kobayashi rate equations, predictions of the stability of diode lasers subject to optical feedback, dependent on the external cavity length have previously been reported [67]. These investigations predict that the stability is dependent on the product of the external cavity round trip time, $\tau$, and the solitary diode relaxation oscillation frequency $\omega_r$. When this product is greater than one, the critical feedback level for entering the coherence collapse regime (from the low feedback regime III) is independent of the external cavity length. For $\tau \omega_r < 1$, the critical feedback level increases dependent on the external cavity length, until for $\tau \omega_r < X_c$ the coherence collapsed state is suppressed and does not occur for any feedback level ($X_c$ is a constant dependent on the parameters of the solitary diode laser). This is shown in figure 4.1, below. Other theoretical analysis of short external cavity diode lasers [65,247] predict similar behaviour with the addition of regions of high frequency oscillations for cavity lengths approaching the condition for suppression of coherence collapse.

Various models based on a rate equation analysis have reported that the critical feedback level for transition into instability (regime III $\rightarrow$ IV) is proportional to the relaxation
oscillation resonance frequency of the solitary diode laser [37,68], and increases with the solitary diode injection current [75]. Stability as a function of the linewidth enhancement factor, the feedback phase and the feedback strength has also been analysed [39,64,76]. These models, however, are only appropriate for long external cavities. Nonlinear dynamics have been investigated for increasing time delay (external cavity length) in refs [166,204,248], but not applied to the stability as a function of feedback strength. Feedback phase instabilities have also been predicted in refs [76,204,248] for long external cavities.

![Figure 4.1. Critical feedback fraction above which coherence collapse occurs, as a function of the external cavity round trip time $\tau$, and the product of $\tau$ and the relaxation oscillation frequency $f_r$. After [67].](image)

Predictions of the stability applicable to short external cavities have been obtained from analysis of the modulation response of the solitary diode laser. This was initially proposed by Helms and Petermann [66], and has more recently been investigated by Pierce et al [249]. It is found that as the external cavity length is reduced the critical feedback level required to generate unstable output in the diode laser oscillates between two values. This is shown in figure 4.2. The lower bound is constant and the upper bound increases with a decrease in cavity length. This is similar to behaviour predicted to occur by a rate equation analysis for conventional optical feedback [40,250], and for phase conjugate feedback (with much longer external cavities) [142,143,145].

Experimentally, various studies have reported the benefits of operating diode lasers with short external cavities [251-254], but no systematic investigation or comparison with the long cavity limit exists.
4.1. Introduction

In the present work, diode laser with feedback stability is examined as a function of several parameters. Specifically, the dependence of the critical feedback level on the diode laser injection current, external cavity length (coarse), and feedback phase is investigated. In addition, the output power versus feedback phase is examined for a range of different feedback levels. In order to determine the effect of the solitary diode laser characteristics the results from two different types of diode laser are compared. The 850 nm STC diode laser (used in the previous chapter) which has an anti-reflection coated front facet and a high reflection coated back facet, and a Nortel 1300 nm quantum well uncoated diode laser are used. Theoretical investigations into the behaviours observed here have been modelled in collaboration by members of the School of Informatics, at the University of Wales.

![Graph showing variation of critical coupling coefficient with external cavity length.](image)

**Figure 4.2.** Variation of the critical value of the feedback coefficient $\kappa$ with external cavity length. After [249].

It is found that suppression of the coherence collapse state for the 1300 nm diode laser occurs for very short external cavities (several mm), as expected. Suppression of coherence collapse for the 850 nm diode laser, however, occurs at much longer cavity lengths (~80 mm). No oscillating critical feedback level is observed for either diode laser. Windows of instability and single-mode operation are observed for variations in feedback phase. The characteristics of the observed states depend on the external cavity length and injection current. Theoretical predictions show similarities with these observations. The stability dependence on the external cavity phase has consequences for the output power. For high (regime V) feedback levels, a triangular variation in output power is observed for increasing feedback phase. A rate equation analysis shows good agreement with the observed power variations.
4.2. Experiment

4.2.1. Set-up

The experimental apparatus is shown in figure 4.3. The solitary diode laser is either a 850 nm, 50 mW, index-guided, quantum-well device (STC #LT50-03U) which has a high reflectance coated back facet and an antireflection coated front facet, or a 1.3 µm, 20 mW, uncoated quantum-well device (manufactured by Nortel). The 850 nm laser is predominantly single-mode (side mode suppression ratio of ~20 dB) when operated above threshold with no feedback. The 1.3 µm laser diode is predominantly multi-mode over all operating currents. The solitary diode output is collimated with a GRIN rod lens and the feedback is provided from a 95 % reflective plane mirror, which is mounted on a piezoelectric stage. The piezoelectric voltage is driven by a variable or ramped voltage, which has been calibrated to the wavelength of the diode laser with an interferometric set-up. A neutral density attenuator is used to control the amount of feedback and an intracavity beamsplitter is used to monitor the system output for the 850 nm diode laser. For the 1300 nm device, the output is monitored from the diode laser back facet. The output is examined on a Fabry-Perot interferometer with a free-spectral-range of 10 or 1000 GHz, an intensity noise spectrum analyser and a power meter.

Figure 4.3. Experimental set-up for (a) 850 nm diode laser and (b) 1300 nm diode laser.
4.2.2. Coupling efficiency

In order to determine if the external cavity length has any effect on the coupling efficiency of the optical feedback field to the laser diode, the coupling efficiency for the 850 nm STC laser diode with a short external cavity has been determined. The same method as used in section 3.2.2 has been applied. The same relationship of slope efficiency and threshold injection current to external feedback fraction is observed. The data shown in figure 4.4 (a and b) determines the 850 nm laser diode short cavity coupling efficiency to be $\eta_c = 0.28 \pm 0.07$.

![Figure 4.4](image)

*Figure 4.4. Slope efficiency (a and c) and threshold injection current (b and d) versus external feedback fraction. Triangles represent experimental data points, lines represent fits from theory. The diode laser in (a) and (b) is the asymmetric coated 850 nm device, the diode laser in (c) and (d) is the 1300 nm uncoated device. The external cavity length is ~10 mm.*

Using the same method for the 1300 nm diode laser, the coupling coefficient cannot be determined. The slope efficiency and threshold injection current versus external feedback fraction are shown in figure 4.4 (c and d respectively). They both show significantly different functionality than curves for the 850 nm diode laser. Although the threshold injection current decreases with feedback fraction, as expected, the relationship is not predicted by the theory.
and no substitution of parameters can generate agreement. In addition, the slope efficiency is found to increase from the solitary diode laser value. The same results are obtained when the output is monitored through the back facet of the external mirror or with an intracavity beamsplitter (for longer external cavities), indicating that the trends are not introduced by the experimental arrangement. The exact reason for the discrepancy between the 1300 nm diode laser behaviour and the theory (equations 2.24, 2.25) is unclear. Because the output from this diode laser is predominantly multi-mode when free-running and also with optical feedback (as examined in proceeding sections), the theory may be inappropriate.

No quantitative value for the coupling efficiency can be predicted from the data for the 1300 nm laser. However, a qualitative estimate can be made by comparing the magnitude in reduction of the threshold injection current to that observed with the 850 nm device. An external feedback fraction $R_{\text{ext}} = 0.8$ injected into the 850 nm device results in a threshold injection current reduced by 30% (to $\sim 0.7 I_{\text{th}}^{dl}$). Similar levels of feedback into the 1300 nm diode laser reduces the threshold current by only $\sim 2\%$ (to $\sim 0.98 I_{\text{th}}^{dl}$). This indicates that the efficiency of the coupling of the external reflection into the 1300 nm diode laser is significantly lower than that obtained with the 850 nm diode laser. This is expected due to loss in reflection off the diode laser front facet ($R_2 = 0.32$ for the 1300 nm laser).

4.3. Stability versus external cavity length

4.3.1. Experimental observations

The behaviour of the uncoated 1300 nm diode laser subject to feedback is observed to agree with theoretical predictions in a number of areas. The feedback fractions that result in transitions from the stable single-mode regime III to the unstable coherence collapse regime IV are shown in figure 4.5. The strong feedback regime V is not observable with this diode laser because the front facet is not coated and thus the feedback power ratio cannot be made large enough. For external cavity lengths longer than $\sim 40$ mm the transition occurs at a constant external feedback fraction (of approximately 0.002), independent of cavity length. As the external cavity length is reduced below 40 mm the feedback level required to destabilise the output increases. For very short external cavity lengths (less than 10 mm), the transition occurs at feedback levels an order of magnitude larger than for long cavities.

The optical frequency spectrum showing the transition from the diode laser with no feedback (which operates predominantly multi-mode), through the stable single-mode...
regime III and into the unstable coherence collapse regime IV, is shown in figure 4.6. Although the diode laser operates on multiple modes free-running and with feedback, each spectrum shows distinct characteristics. This indicates different dynamic states. The free-running laser has a constant output power (with low intensity noise), and the multi-mode spectra with feedback represent dynamic instabilities and chaos.

Figure 4.5. External feedback fraction at which the III→IV transition occurs as a function of external cavity length for an injection current of 50 mA. Data is for the Nortel 1300 nm laser.

Figure 4.6. Optical frequency spectra for 1300 nm diode laser with (a) no feedback, and with an external feedback fraction of (b) 0.002 (regime III), (c) 0.006 (regime III→IV boundary), and (d) 0.010 (regime IV). The external cavity length is 30 mm. $I = 2.2 I_{th}^{dl}$. 
Figure 4.7. External feedback fraction at which the III→IV and the IV→V transitions occur, as a function of external cavity length for the STC 850 nm diode laser at I = 50 mA.

Figure 4.8. Optical frequency spectrum versus external feedback fraction (rows) for the STC 850 nm asymmetric diode laser at three different external cavity lengths (columns). Each spectrum shows a frequency span of ~3 THz.

For the high/low reflectance coated 850 nm diode laser, the critical feedback fraction has a different dependence on the external cavity length. This is shown in figure 4.7, above.
Regime V is attainable with this diode laser due to its low-reflection coated front facet. For external cavities longer than ~200 mm the III→IV transition occurs at an external feedback fraction of approximately 0.0004, independent of cavity length. The IV→V transition also occurs independent of cavity length, however loss due primarily to beam expansion and attenuation means that higher external feedback fractions than actual are recorded for the experimental data shown. As the cavity length is reduced below 200 mm the external feedback fraction of the III→IV transition increases, until for external cavity lengths less than 80 mm no coherence collapse is observed for any values of the external feedback.

The optical frequency spectra for a range of different feedback fractions for three different cavity lengths are shown in figure 4.8. For long cavities there is a distinct transition between the three regimes (stable single-mode regime III, multi-mode coherence collapse regime IV, and single-mode regime V). As the cavity length is reduced the range of feedback fractions resulting in regime IV operation are reduced. For the short 80 mm external cavity no coherence collapse is observed. This is the first time to the authors’ knowledge that the optical feedback fraction for the IV→V transition has been examined systematically.

4.3.2. Comparison with theory

The observations of the cavity length dependence of the critical feedback level for the III→IV transition into coherence collapse for the 1300 nm diode laser, shown in the last section, agrees qualitatively with some theoretical expectations. A constant critical feedback level occurs for cavity lengths longer than ~ 40 mm. This corresponds to a cavity resonance frequency of 3.7 GHz, which is comparable in magnitude to the expected relaxation oscillation frequency of this diode laser at this current. This agrees with the expectation of Schunk and Petermann [67] depicted in figure 4.1. The rapid increase in critical feedback fraction for very short cavities (<5 mm), implying a suppression of coherence collapse, also agrees with expectations.

For the asymmetric coated 850 nm diode laser, the general trend of the critical feedback fraction versus cavity length (for the III→IV transition) is similar to that predicted. It increases with decreased cavity length below a certain value and suppression of the transition into instability is observed for short cavity lengths. However, the cavity length for suppression and for independence of critical feedback level (on cavity length) are much larger that expected (80 mm and 180 mm respectively). The resonant frequency for a 180 mm external cavity is 830 MHz. This is much lower than expected for a relaxation resonant frequency
(at 1.5 $I_{th}^{dl}$). This indicates either that the 850 nm STC diode laser with optical feedback has a uniquely low relaxation oscillation frequency, or that the theory does not hold for this type of diode laser. Results in chapter 6 indicate that the relaxation oscillation frequency of this laser is much higher than this.

Neither diode laser shows oscillating critical feedback level as depicted in figure 4.2 from the research of Pierce et al [249] and others [143,145]. This behaviour may occur on a finer resolution of cavity length than has been investigated in the current experiments. Preliminary theoretical results described by Spencer et al [255] indicate that under certain conditions a stable (non-oscillating) increase in the critical feedback level is predicted.

No theory adequately predicts the behaviour for the strong feedback IV→V transition. The observations indicate that the critical feedback level is independent of cavity length, and that the boundary of suppression of coherence collapse with cavity length is set by the increasing III→IV transition intersecting with this flat feedback level. Further development of the theory is needed to enable it capable of predicting these observations.

4.4. Stability versus injection current

The dependence of the critical feedback fractions (for the III→IV transition) on the injection current of the solitary diode laser have also been examined for both diode lasers. Data for the uncoated 1300 nm diode laser is shown in figure 4.9, and data for the 850 nm diode laser is shown in figure 4.10 (a). The IV→V transition for the 850 nm diode laser is shown in figure 4.10 (b).

For both diode lasers the effect of increasing the injection current is to increase the external feedback fraction required to destabilise the laser diode output at any external cavity length. Thus, the region of chaotic instability is largest for lower injection currents, and higher currents tend to provide greater stability. For long external cavities, the critical feedback fraction tends towards independence of injection current, the dependence increasing with decreasing cavity length. The main difference between the two lasers is that much longer cavity lengths show influence of the transition points on the injection current for the 850 nm diode laser (as expected from the results of the previous section). In addition, this dependence is much greater for all cavity lengths.
4.4. Stability versus injection current

Figure 4.9. External feedback fractions at which the regime III→IV transition occurs as a function of injection current for the 1300 nm uncoated diode laser. Data for three different external cavity lengths is shown.

Figure 4.10. External feedback fractions at which the (a) regime III→IV transition and (b) regime IV→V transition occurs as a function of injection current for the 850 nm asymmetric coated diode laser. Data for three different external cavity lengths is shown in (a).

Various authors have predicted that the critical feedback fraction will increase with increasing injection current [75,76]. This agrees with the experimental observations. The role of the relaxation oscillation frequency is very important for this. The critical feedback fraction is proportional to the relaxation oscillation frequency [37,68,256]. As the injection current
increases, the relaxation oscillation frequency increases, and thus the critical feedback fraction increases. Preliminary theoretical predictions of the critical feedback fraction based on analysis of the modulation transfer function also predict an increase with increasing injection current [257]. Further theoretical analysis needs to be undertaken to determine if quantitative agreement can be reached. No theoretical treatment has been published that is capable of predicting the strong feedback regime $\text{IV} \rightarrow \text{V}$ transition, which is observed to increase logarithmically with injection current.

4.5. Stability versus feedback phase

4.5.1. Experimental observations

Figure 4.11. Stability of the Nortel 1300 nm diode laser as the feedback phase is varied through $2\pi$, for several (a) external cavity lengths, and (b) injection currents. The data points represent transitions between states. The output is stable single-mode (on different longitudinal modes of the solitary diode laser) in regions joined by lines, and multi-mode (unstable) in other regions. The injection current in (a) is 45 mA and the external cavity length in (b) is 10 mm. The external feedback fraction in each case is 0.60.

The effects of varying the feedback phase on the output stability of the 1300 nm diode laser has been investigated as a function of injection current and external cavity length. For parameters (injection current, feedback fraction, and external cavity length) well within either stable or unstable regimes, the feedback phase does not have any effects on the output
4.5. Stability versus feedback phase

longitudinal mode spectrum, and the system operates continuously either on a single-mode or
on a number of modes. However, for parameters close to the boundaries between regimes, the
relative phase of the feedback field dramatically influences the diode laser output stability.

The full experimental parameter space has four dimensions, and a complete
experimental analysis would be extremely time intensive. In order to determine the general
trends of behaviour the feedback fraction is kept constant (as this is difficult to accurately
adjust for short external cavities). The output optical frequency spectrum is then observed as
the feedback phase is varied at a number of external cavity lengths for a fixed injection
current (figure 4.11(a)), and a number of injection currents for a fixed external cavity length
(figure 4.11 (b)). There is no correlation between the exact value of the phase for different
cavity lengths or injection currents (in figure 4.11). Zero feedback phase is defined for an
arbitrary stable state. The optical frequency spectra corresponding to a variation of $2\pi$ for
several cavity lengths in the data set 4.11 (a) are shown in figure 4.12.

Figure 4.12. Optical frequency spectrum for the Nortel 1300 nm diode laser with feedback as
the feedback phase is varied. The sequence shown in each plot represents $2\pi$ phase variation.
The external cavity length is (a) 10mm, (b) 14 mm, (c) 18 mm, and (d) 30 mm. The external
feedback fraction is fixed at 0.60, and the injection current is fixed at 45 mA ($2.5 \, I_{th}^{dl}$). The
frequency span in each spectrum is approximately 1000 GHz.
Figures 4.11 and 4.12 show that as the feedback phase is varied, the output cycles through stable and unstable states. The number of stable and unstable states observed in a \( 2\pi \) phase variation depends on both the external cavity length and the injection current. For long cavity lengths and high injection currents the output is always unstable; phase variations simply alter the characteristics of the multi-mode spectrum (e.g., figure 4.12 (d)), indicating transitions between different dynamic states. As the external cavity length (or the injection current) is reduced, regions of single-mode behaviour are observed for some phase values. The phase values over which the output is single-mode and the number of such single-mode outputs (which have different frequency) observed over \( 2\pi \) phase variation increases with decreased cavity length or injection current. In the limit of short external cavity or low injection current the unstable regions within \( 2\pi \) merge and the output is stable for all values of feedback phase. This is to be expected from the examination of the stability versus injection current and external cavity length in the previous sections of this chapter.

4.5.2. Comparison with theory

A theoretical analysis has been undertaken by R.J. Jones and P.S. Spencer of the University of Wales, with the intention of investigating the behaviour observed in figures 4.11 and 4.12. The analysis follows a two step process. The modes of the system are first found (for each feedback level and possible phase value), and then the stability of each mode determined. The analysis predicts the output state for solutions outside the coherence collapse regime, and the values for boundaries between stable and unstable (chaotic) operating regions. The theory is based on the Lang-Kobayashi rate equations and is described in more detail in reference [258] (also see [259]).

The theoretical prediction is shown in figure 4.13. Windows of instability are observed in the parameter space of feedback fraction and feedback phase. The regions of instability are found to increase with external cavity length, so that in the long cavity limit, the instability regions merge together. The range of feedback fractions resulting in unstable operation is observed to increase with increased external cavity length.

The experimental observations have considered a fixed feedback fraction, which represents a horizontal line through each of the plots (a-d) in figure 4.13. The injection current is kept constant in the model. Agreement between experiment and theory occurs in the prediction of instability regions for variations in feedback phase. Disagreement occurs in the
theoretical prediction of only one stable region (and one unstable region) within a $2\pi$ phase shift, and a stable solution existing for any value of the feedback fraction.

Figure 4.13. Theoretical prediction of stability regions in the parameter space of feedback fraction (external mirror reflectivity) and feedback phase. Shaded regions represent multimode instability, unshaded regions are stable single-mode output. The external cavity length is (a) 18 mm, (b) 12 mm, (c) 6 mm, (d) 4 mm. See ref [259] for full list of model parameters.

4.6. Output power versus feedback phase

4.6.1. Experimental observations

The variation of average (1 ms) output power as a function of feedback phase and feedback fraction has been examined for both diode lasers. The data in figure 4.14 is for the STC 850 nm diode laser. The 1300 nm diode laser shows similar behaviour but the strong feedback regime V is not attainable. The optical frequency spectra corresponding to each feedback level (a-h) in figure 4.14 is shown in figure 4.15.
For low feedback fractions (corresponding to stable-single-mode operation), the output power varies sinusoidally with feedback phase (a,b). As the feedback fraction increases and there is a transition into multi-mode output (figure 4.15 (c)), the output power versus feedback phase deviates from sinusoidal (figure 4.14 (c,d)). Well within the coherence collapse regime, representing fully developed chaos, the output power is constant with feedback phase (e,f). For strong regime V single-mode feedback, the output power is found to vary with a triangular waveform with a period slightly greater than 2\(\pi\), as depicted in (g,h).

The triangular variation of the output power with strong feedback has been examined as the external cavity length is varied. This is shown in figure 4.16, below. Although the sinusoidal variation of the output power with weak feedback is attenuated strongly as the external cavity length is increased, indicating the effect of the spatial coherence of the diode.
4.6. Output power versus feedback phase

laser output, the triangular variation for strong feedback continues to much longer cavity lengths.

Figure 4.15. Optical frequency spectrum (at a resolution of the external cavity mode spacing) of the diode laser for each of the feedback fractions (a-h) used in figure 4.14. Spectra are plotted on identical vertical scales shifted vertically for clarity. The stable single-mode spectra (a,b,g,h) have been cropped.

Figure 4.16. Output power versus feedback phase for a range of external cavity lengths: (a) 20 mm, (b) 50 mm, (c) 200 mm, (d) 400 mm. The external feedback fraction is 0.75.
4.6.2. Comparison with theory

A sinusoidal variation of the output is to be expected for the very low feedback regime I from accepted diode laser with optical feedback theory. This will occur because the gain and threshold injection current are directly dependent on the feedback phase [44]. However, in the current experimental arrangement, a sinusoidal variation in output power is observed at feedback levels corresponding to regime III.

![Figure 4.17. Theoretical prediction of the output power as a function of feedback phase for a range of feedback fractions representing operation in (x) regime V, (y) regime IV, and (z) regime III.](image)

Based on the theoretical analysis of the last section the model has been applied to the output power variations [258]. Theoretical predictions are shown in figure 4.17. For low feedback fractions, the system only supports one mode, and this mode is always stable. Small changes in the external cavity phase then result in a linear change in the emission frequency. This causes a sinusoidal variation in the carrier density and consequently in the steady state output power. In regime IV the output power is chaotic in time and the coherence length of the laser output is very small. Therefore, adjusting the length of the external mirror has no effect. In the strong feedback regime, the system supports multiple modes, which are stable.
for different ranges of the feedback phase. The system operates around the mode with the minimum linewidth, but to do so has to change modes as the external cavity phase is varied. The sawtooth output power variation arises as the system jumps between adjacent modes.

4.7. Summary

The results presented in this chapter have significant implications for several reasons. It is important to understand how the behaviours of a feedback system are influenced by the controllable variables (feedback fraction, external cavity length, feedback phase, and injection current). Many applied diode laser with feedback systems use feedback from short (or integrated) external cavities of various lengths. Many systems operate with unwanted feedback from elements of various distance (and variable reflectivity) to the front facet of the diode laser, for example, from collimating lenses, fibre end faces, and fibre optic couplers. Variations in optical elements on the scale of the wavelength of light are often encountered in real systems due to mechanical vibrations and air currents. This effects the feedback phase from both system elements and unwanted reflections. In addition, a range of injection currents relative to threshold is used in any diode laser system.

The results of this chapter indicate that the feedback regimes for a given diode laser depend on a number of factors. For different solitary diode lasers, significantly different parameters lead to stable (and unstable) operating points. If a feedback system is operating close to the boundary between feedback regimes, then minor variations in feedback phase, external cavity length, or injection current, can drastically effect the output stability or cause a minor deviation to the output power. This indicates the necessity for the feedback characteristics of a particular diode laser to be known before an optical feedback system can be designed for a given application.

The observations presented in this chapter indicate the complexity of optical feedback systems. The many parameters of a system effect the output in a complicated manner and this is difficult to simulate theoretically. It is also difficult to get quantitative agreement between experiment and theory as there are a large number of parameters that must be estimated. The two diode lasers examined in this chapter are observed to behave very differently with respect to the controllable variables (injection current, feedback fraction, feedback phase, external cavity length). Internal diode laser parameters used in simulations include the gain coefficient, the linewidth enhancement factor, the facet reflectivities, the carrier density at threshold and
transparency, the carrier lifetime, the photon lifetime, the active region volume, the relaxation oscillation frequency and damping, the wavelength, and the internal loss factor. Parameters known for the two lasers are the facet reflectivities, carrier and photon lifetimes, internal loss factors, and wavelength. In each of the known parameters (see appendix A) there is a large uncertainty. Other parameters can be estimated for a given diode laser by experimental methods, though this has not been carried out in the current work. The number of parameters indicates the complexity of the system. Small variations to many of the variables in the theoretical simulations can result in significant changes to the theoretical predictions. In order to understand the mechanisms that lead to the different results observed for the two different diode lasers examined in this chapter, a more accurate description of the laser diode internal parameters and further analysis of the models for a larger range of parameters (including strong feedback models), is needed. A theoretical understanding of the reasons for the better stability of the STC 850 nm diode laser compared to the Nortel 1300 nm device would be very beneficial.
Chapter Five: Optical Injection and Optical Feedback

5.1. Introduction

The injection of a single-frequency source into the cavity of a semiconductor laser has been demonstrated to dramatically influence the diode laser output [93,94,97,102,106]. Similar to optical feedback, such optical injection has various effects depending on the level of the injected signal and the detuning between the master and slave laser frequencies. For strong injection, the dominant effect is to lock the frequency of the slave diode laser to the master laser frequency [109]. For weak injection a range of distinct output states are possible, including dynamic instabilities [84], four-wave-mixing [111], relaxation oscillation enhancement, and injection locking [102]. Injection locking of diode lasers is used in many practical and applied systems, such as spectroscopy and optical communications, which utilise the enhanced frequency stability and narrowed linewidth of the locked state [260,261].

Although diode lasers that are subject to either optical injection or optical feedback have been extensively studied, the topic of diode lasers that are simultaneously subject to both optical injection and optical feedback has only received limited attention [167,262,263]. The transient dynamics of a diode laser subject to both weak optical feedback and optical injection have been examined in ref [167]. Both turn-on jitter and frequency jitter were strongly reduced by adjusting either the external cavity length or the detuning between the injected signal frequency and the diode laser with feedback frequency. The phase locking of the signal from a broad-area diode laser with optical feedback by another single-mode external cavity diode laser has been demonstrated. It was found to improve both the spatial and spectral radiation field of the slave diode [262]. The effect of delayed optoelectronic feedback on the output of an injection locked single-mode diode laser has also been reported. Optoelectronic feedback was used to control the dynamic state of the output power. Negative feedback configurations (representing out-of-phase carrier re-injection) were found to widen the injection locking region and reduce the regions of instability; in-phase feedback was observed...
to generate a tunable modulation on the output power signal at multi-gigahertz frequencies [263].

The current study gives a systematic examination of the relative effects of simultaneous optical injection and optical feedback on the output characteristics (stability and locking range) of a diode laser. This differs from the earlier investigations in that only optical feedback (as opposed to optoelectronic feedback) is considered. Additionally, the effects are examined for a broad range of optical feedback powers (from weak regime III feedback to very strong regime V feedback) and injected signal powers. It is shown that strong optical injection from an external source overrides coherence collapse in a laser diode just as strong self-injection is observed to prevent coherence collapse in an external cavity laser system. These ideas can be generalised to proposals for integrated laser diode designs that are insensitive to optical feedback up to levels well above those that normally cause coherence collapse.

The rendering of a diode laser insensitive to optical feedback by the means of an optically injected signal offers various advantages to existing methods. In a practical optical system there will always be unwanted feedback, arising from, for example, fibre optic end facets, couplers, or optical discs. Very low levels of feedback (~10^{-5} % of the laser diode output) are known to influence the laser stability, and may cause operation in the unstable coherence collapse regime. Such broad noise, multi-mode output renders the diode laser unsuitable for most applications. Various schemes have been proposed to combat this transition to instability/chaos [71,264]. These include using expensive optical isolators, or high quality anti-reflection coatings on all surfaces, and careful control of diode laser and system design parameters. In addition, there are various methods of chaos control, such as high frequency injection [265,266] or dynamic targeting [267], that (through electro-optic feedback) force a system operating in a chaotic state to operate in a more stable state - typically one with a time varying output power (limit-cycle behaviour). No study has been reported, to the authors’ knowledge, on the relative merits of using an injected optical signal for controlling the coherence state of the output of a diode laser.
5.2. Experiment

5.2.1. Set-up

The experimental set-up is shown in figure 5.1. The slave diode laser is an index-guided quantum-well GaAlAs device (STC #LT50-03U, 850 nm, 50 mW cw) as used in the previous chapters, which is collimated with a Gradient Index rod lens (Melles Griot #06LGT214). The feedback is provided from a dielectric coated plane mirror ($R_{mirror} = 0.95$) placed approximately 300 mm from the diode laser. A variable attenuator controls the amount of feedback. Intracavity beamsplitters are used for output coupling and to inject the master laser signal from a commercial tunable external cavity diode laser (New Focus #6126). The diagnostics are a power meter (Ophir Nova Display), a 10 or 1000 GHz FSR Fabry-Perot interferometer, an Optical Frequency Spectrum Analyser, and a fast (~ 3 GHz) photodiode (#BPW28) connected to a radio frequency spectrum analyser (Textronix #2754P). The injected signal is aligned by maximising the injection locked power outside the cavity (at output 1). The injected signal power (for strong injection) is typically several mW, which is comparable with the external cavity system intra-cavity power.

Figure 5.1. Experimental apparatus for injection locking of diode laser with feedback.
5.2.2. Coupling efficiency

Similar to the case of a diode laser with optical feedback, the efficiency of the coupling between the injected master laser signal and the slave diode laser active layer is difficult to accurately determine, particularly when the laser diode is also subject to a feedback field. An estimate can be made on the injection efficiency, $\eta_{inj}$, by operating the diode laser as a photodiode; ie the diode is disconnected from its current source, and short circuited with a load resistance. The photocurrent induced by the injected field is then measured with a voltmeter. The induced photocurrent, $I_p$, is related to the incident optical power, $P_{inc}$, by [268]

$$P_{inc} = \frac{hf}{e\eta_{pd}}I_p$$

(5.1)

where $\eta_{pd}$ is the photodetection quantum efficiency, which represents the probability that a single photon incident on the device generates a photocarrier pair that contributes to the detector current, and can be written

$$\eta_{pd} = (1 - R)\zeta[1 - \exp(-\alpha d)]$$

(5.2)

where $R$ is the front facet reflectivity (~0.05), $\zeta$ is the fraction of electron hole pairs that contribute to the detector current (typically 0.8 [268]), $\alpha_{abs}$ is the material absorption coefficient (~10$^3$ cm$^{-1}$ for GaAs [176]), and $d$ is the photodetector depth (the length of active cavity is 490 $\mu$m for the STC diode laser).

The injection coupling efficiency is then given by the ratio of the incident power calculated from the photocurrent (equation 5.1) to the external injected power $P_{ext}$, which is measured in front of the collimating lens, ie

$$\eta_{inj} = \frac{P_{inc}}{P_{ext}}$$

(5.3)

It represents the efficiency by which the injected photons are coupled into the laser cavity and not lost via transmission through the GRIN lens and spatial mismatch between the injected mode and the slave laser output mode.

Aligning the system for highest photocurrent, by optimising the system with the slave diode laser as a photodiode, does not correspond to the best coupling between the internal laser fields inside the active layer. The optimum coupling between the injected master laser and the internal slave laser fields generates the largest interaction between the master and slave lasers, ie the largest locking bandwidth for a given injected power and the highest single-mode output power at the centre of the locking bandwidth. This typically occurs at a detuning of approximately $+ 4$ GHz (defining positive detuning as injection frequency greater
than slave frequency), and varies with injected signal strength. The system is thus aligned first to achieve the maximum locked output power and then the slave diode laser is disconnected from its power source and the photocurrent measured as a function of injected signal strength. The alignment for highest photocurrent does not correspond to the highest laser field coupling as it does not match the two laser output modes (slave and coupled master). The slave laser is a single narrow-waveguide device that only supports one spatial mode. Both fields are thus coupled into this mode but the maximum photocurrent generated represents coupling of the injected field into the cladding layers, which do not support the fundamental spatial mode of the diode laser.

Figure 5.2. (a) Induced photodetection voltage as a function of external injected signal power (measured in front of the collimating optic). (b) Incident power (calculated in equation 5.1 from the measured induced photocurrent) versus external injected signal power. Slope of best fit (solid line) represents the coupling efficiency (equation 5.3).

The induced voltage across the photodetector is shown in figure 5.2 (a) as a function of injected power. The incident power calculated from the induced voltage (equation 5.1) is shown as a function of external injected power in figure 5.2 (b), for $\eta_{pd} = 0.29 \pm 0.07$. The slope of this graph represents the injection coupling coefficient, which is calculated to be $\eta_{inj} = 0.12 \pm 0.02$. This agrees with the expectation that the injection efficiency is significantly lower than the coupling efficiency for the feedback field (calculated in the section 3.2.2 to be $\eta_c = 0.28 \pm 0.02$) based upon the differences in the spatial modes between the slave and master lasers. An estimation on the lower limit of the injection coupling efficiency has been obtained by observing the injected power coupled into (and out of) the diode laser when the
slave laser is turned off (taking account of the front facet reflectivity). The lower limit is 0.05, which agrees with the determination from the photocurrent measurements. This also agrees with other values for the injection efficiency reported in the literature [85].

5.3. Strong Optical Injection

5.3.1. Spectral characteristics

The effects of strong optical injection on the spectral and dynamic properties of the slave laser, dependent on the initial state of the master and slave laser systems, are considered. A single-mode signal from the (master) tunable diode laser is injected into the cavity of the slave laser diode, which is operating with feedback. The feedback is aligned first, before applying the injection. The master laser signal is tuned close to the frequency of the slave diode laser with feedback (or to the mode with largest amplitude for multi-mode operation). The resultant optical frequency spectrum is then observed for a range of the injected signal powers and detuning between the two laser systems.

The observed spectral characteristics of the injected output of the STC laser for several different values of the injected signal and external feedback fraction are shown in figure 5.3. The detuning between master and slave frequencies is constant (~ +4GHz) in each column of the figure. The first row of the figure shows the optical frequency spectrum of the diode laser with varying optical feedback and no injection. Injecting a moderately strong signal ($P_{ext} / P_{out} = 0.3-0.8$) into the diode laser with feedback, as shown in the third row of the figure, results in a distinct output state that comprises operation on multiple modes spaced by approximately 4 GHz. This instability is induced by the competition between the slave diode laser longitudinal mode frequency and the injected signal frequency. It has similar appearance independent of the feedback level. (Note that the external injected power ratio $P_{ext} / P_{out}$ does not include the injection coupling efficiency).

Injecting a much weaker signal ($P_{ext} / P_{out} = 0.05-0.1$) into the slave laser with feedback system (row two of the figure) is also shown to induce unstable output. However, in this case the output spectra is dependent on the feedback level, and shows characteristics of the spectra of both the diode laser with feedback and no injection (first row) and the diode laser with feedback and moderate injection (third row). Thus, the convoluted spectral output for weak feedback arises due to a competition between the instability mechanisms for feedback and
5.3. Strong optical injection

those for injection. In the third row the injection field dominates and so the output has characteristics of injection induced instability only.

Figure 5.3. Optical frequency spectra for injection locking of slave feedback system by a single-mode master laser. Each column represents a particular value of the external feedback fraction into the slave laser (as given in figure). The first row shows the initial slave laser output with no injection. The next three rows represent increasing external injected power ratios (as indicted in the figure). The detuning between injected and slave laser frequencies is fixed at ~4GHz. The injection current of the slave laser is 55 mA (~1.7 $I_{th}^{dl}$).

Further increase in the injected signal ($P_{ext} / P_{out} = 0.8-1.5$) results in injection locking behaviour. This is found to occur regardless of the value of the feedback (and hence the coherence state of the diode laser before injection). However, larger injection powers are required to attain this state in the presence of feedback. Thus, if the feedback level into the slave laser diode is sufficient to cause coherence collapse, such as induced by external mirror misalignment, or by intra-cavity attenuation, then injecting a single-mode signal of sufficient
power and detuning causes the slave laser to operate on a single longitudinal mode, with similar side mode suppression to the free-running regime V laser diode. In this state the injection induced stability is a far stronger mechanism than the feedback induced instability. This is found to occur at any point in the chaotic regime IV.

![Figure 5.4](image)

**Figure 5.4. Optical frequency spectrum of the injected master laser operated multi-mode with optical feedback (first column), unlocked state of the slave laser with optical feedback (second column), and output state of the slave laser (third column).**

The system is further complicated by operating the master laser in an unstable state. Extra optical feedback from an additional mirror is introduced into the tunable ECDL so that it produces multi-mode output. This multi-mode signal is then injected into the slave diode laser, which is operating on a stable single-mode. It is found that for very low injected power compared with the slave laser free running power, there is no apparent effect on the output spectrum at any detuning. This is illustrated in figure 5.4, above. If the injected power is increased there is a transition to an unstable state in the slave laser, similar to that observed in the master laser. If the multi-mode master laser signal is injected into the slave laser diode with optical feedback appropriate to regime IV unstable output, then low injection levels
result in multi-mode output with characteristics of the feedback induced instabilities in the slave laser, and strong injection results in a multi-mode output with characteristics of both the unstable master and unstable slave state.

When the STC diode laser is replaced with the SDL diode laser (the second diode laser used in Chapter 3) similar behaviour is observed. Injection locked single-mode output is attainable at any value of the feedback fraction (indicating any state of the laser diode with feedback) provided that the injected signal is strong enough. This includes the multi-mode state of the SDL laser that was observed at high currents for symmetric on-axis alignments. Therefore the phase-locked state induced by strong optical injection occurs independent of initial instabilities and independent on the method by which the instability is induced (whether through spatial/ spectral hole burning or conventional regime IV behaviour).

The fact that a dynamically unstable diode laser can be forced to operate on a single-frequency through optical injection may seem an obvious extension of the behaviour of injection locked diode laser systems; as free-running diode lasers that operate multi-mode are readily locked to external sources. However, such an application of optical injection has not been referred to or reported in the literature, to the authors’ knowledge. The role of the feedback induced instability and how its competes with the injected field was also unknown.

### 5.3.2. Theoretical injection locking range

The locking range, $\Delta f_{IL}$, for a diode laser subject to injection from another diode laser has been derived as the steady state solution of the rate equations for injection locking (in section 2.3), and is given by [93,94]

\[
\frac{c\sqrt{1+\alpha^2}}{4\pi nL} \sqrt{\frac{P_{\text{out}}}{P_{\text{inj}}}} \geq \Delta f_{IL} \geq \frac{c}{4\pi nL} \sqrt{\frac{P_{\text{inj}}}{P_{\text{out}}}}
\]

(5.4)

where $P_{\text{out}}$ and $P_{\text{inj}}$ are the injection locked output power and the injected power (inside the slave laser cavity) respectively. Reasonable agreement between this prediction and experimental data has previously been produced by a number of separate authors [85,94,104].

In terms of the experimentally measurable quantities, the injection term is given by

\[
\frac{P_{\text{inj}}}{P_{\text{out}}} = \eta_{\text{inj}} \frac{P_{\text{ext}}}{P_{\text{out}}} = \eta_{\text{inj}} (1 - R_{bs})^2 \frac{P_{\text{out2}}}{P_{\text{out1}}}
\]

(5.5)

where $P_{\text{out1}}$ and $P_{\text{out2}}$ are the output powers measured at output 1 and output 2, respectively with the external mirror blocked (figure 5.1).
The model represented by equation 5.4 needs some modification to be capable of predicting the locking range for a diode laser subject to optical injection (from another diode laser) and optical feedback (from an external reflector) simultaneously. Simply setting $L$ as the external cavity length, $l$, in the equation above has the desired effect, i.e., the locking range is greatly reduced due to the increased round trip time in the external cavity, but the behaviour with changing levels of optical feedback is not predicted.

The phase rate equation for a diode laser with feedback and injected fields may be written as [45,85]

$$\frac{d\phi(t)}{dt} = -\left(\omega_{inj} - \omega_0(N)\right) + \frac{1}{2\tau_p} \left(\frac{P_{inj}(t)}{P_{out}(t)}\right) \sin\left[\omega_{inj} - \omega_0\right] + \left[\phi(t) - \phi(t)\right]$$

$$+ \frac{\alpha}{2} \left(G(N) - \frac{1}{\tau_p}\right) P_1^2 - \kappa \sqrt{\frac{P(t-\tau)}{P(t)}} \sin\left[\omega_0 \tau + \phi(t) - \phi(t-\tau)\right]$$

(5.6)

where all variables have been previously defined (see appendix B).

Nonlinear gain saturation and the dependence of the gain on the carrier density have been neglected in equation (5.6) for simplicity, and because the gain/loss terms (third component) are negligible compared with the feedback and injection terms in the steady state. Equation (5.6) can thus be solved to obtain the locking range, $2(\omega_{inj} - \omega_0(N))/2\pi$, as

$$\Delta f_{il} = \frac{1}{2\pi \tau_p} \left[\sqrt{\frac{P_{inj}}{P_{out}}} - \frac{P_o}{P_{out}}\right].$$

(5.7)

In terms of the measurable parameters

$$\Delta f_{il} = \frac{1}{2\pi \tau_p} \left[\sqrt{\frac{P_{inj}}{P_{out}}} - \frac{1-R_2}{\sqrt{R_2}} \left(\eta_{inj} R_{ext}\right)\right].$$

(5.8)

The values of $\eta_{inj}$ and $\eta_c$ used are as determined in section 5.2.2.

The relationship between frequency locking range, injected power and optical feedback is thus determined by two competing terms: the first representing the injected field, the second the optical feedback field. If the injection term dominates the optical feedback term, then the locking range is positive and locking of the slave laser diode with optical feedback to the injected laser is possible. If, however, the optical feedback term is dominant, then locking to the external injection source is not possible, because the locking range is negative. The system may be interpreted, in this case, as being self-locked. This is unlike the case for injection locking a free-running diode laser with no optical feedback, where at any particular injection ratio ($P_{inj} / P_{out}$) there is always a detuning between the master and slave that will produce a frequency locked output state. If optical feedback is present at any
particular level there is a minimum injection power below which injection locking is not possible, independent of the detuning.

This is illustrated in figure 5.5, which shows the frequency locking range as a function of external injection ratio \( \left( \frac{P_{\text{ext}}}{P_{\text{out}}} \right) \) for a number of different external optical feedback fractions \( (R_{\text{ext}}) \). As the feedback level is increased much larger seed ratios are required to generate locking ranges of comparable magnitude to that possible with the free-running diode laser with no feedback. By analogy with the analysis of Petitbon et al [94], retention of the gain terms in equation (5.6) and its solution along with that for the photon density is expected to give an upper and lower bound on the injection locking bandwidth, where equation (5.8) defines the lower bound. The injection locking bandwidth then lies in the range:

\[
\sqrt{1 + \alpha^2} \rho \geq \Delta f_{\text{IL}} \geq \rho
\]

where \( \rho \) is defined by equation (5.8).

![Figure 5.5. Injection locking range versus external injection power ratio for the case of no feedback and for a number of different values of the external feedback fraction (from equation 5.8).](image)

**5.3.3. Experimental injection locking range**

The range of frequencies of the master laser that allow injection locking as a function of the external injection power ratio and the external feedback fraction has been examined experimentally. Feedback (on-axis) is first aligned into the slave diode laser cavity at a certain value. The single-mode master laser signal is then injected into the slave laser diode with
feedback, and the master frequency tuned across the slave diode laser with feedback centre frequency while observing the output optical frequency spectrum with a Fabry-Perot interferometer at various free-spectral-ranges.

Figure 5.6 (a) shows the experimental locking range as a function of the external feedback fraction for a number of different external injection power ratios. The locking range for a fixed seed power is found to rapidly decrease from that of the laser diode without optical feedback as the level of optical feedback is increased. As expected, for any particular optical feedback level there is a particular injection power ratio below which the slave laser diode with feedback will not lock to the injected signal.

The curves predicted from the theory (equation 5.8) are shown in figure 5.6 (b). Normalised quantities have been used for the frequency locking bandwidth in order to concentrate on the relative decrease in the injection locking bandwidth with increasing levels of optical feedback. It is the relative values of the coupling coefficients, that determines this rate of decline. Good qualitative agreement between theory and experiment is demonstrated.

![Graph showing experimental and calculated frequency locking range](image)

**Figure 5.6. (a): Experimental frequency locking range as a function of external feedback fraction ($R_{ext}$) for four injected power ratios: $P_{inj}/P_{out} = 0.66$ (w), 0.45 (x), 0.33 (y), and 0.15 (z). (b): Normalised calculated locking range predicted using equation (5.6). Injection current of slave laser is 50 mA.**
5.4. Transitions into instability

In the previous section, the effect of optical injection on the laser diode with optical feedback was examined. It has been demonstrated that an optically injected field can overcome the instability induced by the optical feedback field at any given feedback ratio if it is sufficiently strong. For these previous results (depicted in figure 5.3) the optical feedback was first applied and the injected signal tuned close to the frequency of the diode laser with feedback. As the feedback shifts the operating frequency, the injected signal was tuned to a different frequency for each feedback level.

This section considers the effects of the injection levels on the tolerance of the system to external feedback; ie, the injection is added before the feedback. This more accurately describes the behaviours that would be encountered in a practical system. The master laser is injected into the slave diode laser isolated from feedback, and then tuned to the solitary diode laser frequency until locking occurs. The detuning is set at the middle of the locking bandwidth (which varies with injected signal strength but is approximately +4 GHz), and the minimum injection power ratio required for phase locking recorded. If feedback is then introduced into the locked system, the output destabilises and the optical frequency spectrum has characteristics of an injection-induced instability (similar to those depicted in figure 5.3 for moderate injection levels). Phase locking can then be reattained by increasing the injected signal power.

Similarly, if the system is locked at any particular injected power, and then feedback increased from zero, a feedback fraction is reached beyond which there is a transition from locked to unstable behaviour. The external feedback fractions resulting in such a transition are shown in figure 5.7 (a), below, as a function of injection power ratio. Large external feedback fractions ($R_{ext} > 0.4$) require very strong injection ($P_{ext} > 4 P_{out}$) for locking to be retained. These injected powers are significantly higher than those required previously (section 5.3.1).

Increased injection power is required to retain the phase locked state because the current procedure results in intermodal optical injection, as opposed to intramodal injection used previously (in section 5.3.1). In the current experiment the injected master signal frequency is not shifted from its original position close to the solitary diode laser central mode. However, the lasing mode of the diode laser is shifted due to the presence of feedback by as much as several nm for high $R_{ext}$ (as demonstrated in figure 3.17). Thus the injected signal is effectively tuned to a side mode of the laser diode with feedback. This results in an increased injection power necessary to achieve locking [114,269].
In figure 5.7 (b) the external injected power and the external feedback fractions are converted into coupled injected power and internal feedback fractions respectively, ie the differences in coupling efficiencies are considered. If the two competing fields inside the diode laser contributed equally to the output state then the slope of this graph would be ~1. This shows that the feedback field is the dominant inducer of instability inside the diode laser active layer even though the injected field power is significantly stronger.

![Figure 5.7](image_url)

**Figure 5.7.** (a) Injected signal power required for single-mode injection locked output versus external feedback fraction. (b) Parameters in (a) converted to internal injection power ratio and internal feedback fraction from their respective coupling efficiencies.

### 5.5. Weak injection

Although this work has concentrated on the effects of strong optical injection combined with feedback directed towards attaining single-mode operation through the injection locked state, there are a number of other states observed for very weak optical injection. As discussed in section 2.4, a diode laser when subject to weak injection from another diode laser source will experience a number of different dynamic states dependent on the injected power ratio and detuning. These states include four-wave-mixing, injection locking, relaxation oscillation frequency enhancement, and various dynamic instabilities. Such states have been observed in the current work for weak injection. This behaviour is typically depicted by a two-dimensional map of stability in the parameter space of detuning and injected power; as for example in figure 2.8 from the research of Simpson et al [109]. The additional presence of...
optical feedback in the slave laser diode has the effect of adding an extra-dimension to this parameter space and significantly complicating the behaviour. A complete experimental investigation of this parameter space would thus be experimentally time intensive.

General features of the effects of the feedback have, however, been investigated. The effect of the feedback is to increase the injected seed power necessary to cause a change in the dynamic state of the slave diode laser. Regions of multi-mode behaviour are observed at the boundaries of transitions into injection locking. Regions of instability are introduced at feedback levels that induce a coherence collapsed state in the slave laser, and these have distinct characteristics as depicted in figure 5.3. Four-wave-mixing, as shown in figure 2.9 is observed at ranges of detunings and injected powers for the solitary diode laser with no feedback. However, this state is not observed when feedback is introduced into the slave laser, indicating that the competition between the feedback and injected fields is too strong to form a stable refractive index grating within the semiconductor active layer. Regions of relaxation oscillation enhancement are also observed in the presence of optical feedback.

5.6. Integrated devices

The observations of diode lasers subject to optical injection and optical feedback indicate the possibility for several integrated device designs. An integrated semiconductor chip that is insensitive to additional optical feedback would find application in a number of areas. As outlined in section 5.1, a problem in any optical system is that unwanted feedback always exists and can cause undesirable effects. Most importantly, the feedback can force a diode laser to operate chaotically, which means that the laser is useless for most applications in communications and optical data storage. This is most commonly alleviated by the use of expensive optical isolators, antireflection coated surfaces, and often by design of system components. These solutions are often prohibitively expensive for many applications.

Four possible examples of a feedback insensitive system are shown in figure 5.8. Depicted in (a) is simply a laser diode with strong feedback (regime V), where the feedback is introduced into the opposite facet from the output. In this device the strong feedback from facet 1 acts to self lock the diode laser, and, providing that the feedback can be made large enough in comparison with any other reflections entering the diode laser from facet 2 (which may lead to coherence collapsed behaviour), then the output will remain single-mode. The back facet 1 of the diode laser must be anti-reflection coated to maximise the feedback from the external
mirror in order that regime V single-mode behaviour is attained. The front facet 2 should ideally be coated with as high a reflectivity as possible in order to minimise unwanted feedback and still allow the generation of a useable amount of output power. There is thus an ideal combination of facet coatings that involves a trade-off between output power and susceptibility to stray reflections.

Figure 5.8. Examples of diode configurations insensitive to additional feedback. (a) Regime V ECDL. Output is from facet 2 (no coating), and anti-reflection or low-reflection coated facet 1 receives feedback from high reflection coated mirror. (b) Master (LD1)/slave (LD2) pair. Facet 1 and 3 are HR coated, facet 2 is AR coated and facet 4 is AR or uncoated. LD1 is operated at much higher current than LD2. (c) Integrated device version of (a) with an active laser section (AL) and a passive waveguide section (PW). Facet 1 has a high reflectance coating for strong optical feedback, and facet 2 is antireflection coated. This device is called an OFILD - optical feedback insensitive laser diode. (d) Integrated device version of (b) with two active layer sections (AL) separated by a passive waveguide section (PW). GL is 0.23 pitch GRadient INdex lens, and Glx is a 0.29 pitch GRadient INdex lens.
In figure 5.8 (b) a master diode laser (LD1) is used to inject a signal into the slave diode laser (LD2). Facet 1 and 3 are high reflection coated, and facets 2 and 4 are anti-reflection or low-reflection coated. In this configuration no isolation is required between the master and slave lasers as the strong feedback from facet 3 into LD1 ensures that this diode laser operates in the stable single mode regime V. If feedback from a distant reflector is sufficient to cause diode laser 2 to operate in the coherence collapsed state, then the injected signal from the laser diode with feedback comprising diode laser 1 and facet 3 will act to lock the two laser diodes in frequency, resulting in a stable single mode output.

Although the coherence collapsed signal of diode laser 2 is being injected into diode laser 1, operating diode laser 1 at a much higher power (and due to the reflectivity coatings) ensures that the injected field is much stronger than the optical feedback field. The consequence of this large power difference is that there is no change to the output stability, as the experiments have shown. This is similar to a cleaved coupled cavity diode laser, which typically provides longitudinal mode selection due to the difference in length of the two diodes. Such diode lasers are still sensitive to unwanted feedback, although less so than a solitary diode laser.

The first of these designs is suitable for fabrication as an integrated device using an active laser section and a passive waveguide section with a total length of a few millimetres as depicted in figure 5.8 (c). Such a device has been termed an Optical Feedback Insensitive Laser Diode (OFILD). It is based upon the same principals as the system depicted in figure 5.8 (a); ie the strong feedback from the back section of the device acts to self-lock the laser output. Again, the optimum relative facet coatings must be determined. Similar device structures (consisting of an active layer region integrated with a longer passive wave-guiding section) have been proposed and demonstrated previously [270-276]. In these devices the waveguiding section has been used to narrow the lasing linewidth, and reduce the threshold injection current. No such device design with the application of the OFILD has previously been reported. The second device design may also be suitable for fabrication as an integrated device comprising two active laser sections separated by a passive waveguide section as depicted in figure 5.8 (d).
5.7. Summary

The results presented in this chapter are important for several reasons. Firstly, the similarities and differences between the instabilities induced by optical feedback and optical injection have been examined. The effects of weak feedback (regime IV) and of weak injection outside the locking range on the output frequency have been shown to be similar. In both cases multi-mode spectra are observed. For feedback, the mode spacing of the adjacent additional modes is that of the external cavity frequency. For injection, the mode spacing is that of the detuning between the injected signal frequency and the slave laser frequency. The optical spectrum has characteristics of either the feedback induced instability, the injection induced instability or a combination of both, depending on the relative levels of feedback and injection.

Secondly, it is important to examine the simultaneous effects of optical injection and optical feedback because many systems that use injection locking, generally to control the frequency profile of a higher power device with a lower power narrow linewidth laser, are used in optical systems with unwanted feedback. The results of section 5.4 show that as the feedback is increased higher injection powers are required to maintain the injection locked state, and that the injection field dominates the optical feedback field inside the gain region. Susceptibility to optical feedback is different in an injection locked laser than a free-running solitary diode laser.

Thirdly, the results have indicated that injection may be used to make a diode laser unsusceptible or less susceptible to external feedback. This result has been extended to integrated device design as described in the previous section. Such a device would find application is a large number of areas.
Chapter Six: Phase Conjugate Feedback

6.1. Introduction

As outlined in section 2.4, the diverse effects of phase conjugate feedback on the operating characteristics of diode lasers have been examined in detail both experimentally and theoretically. Theoretical studies on diode lasers with PCF have shown that the spatial and temporal phase reversal induced by the phase conjugate mirror (PCM) incite, for certain ranges of PCF, dynamic instabilities which are distinct from those encountered in a COF system [24,137,138,140-143,146]. Diode lasers subject to PCF have been shown to take different routes to instability than for COF [137], and differences are observed in the length dependence of the critical reflectivities for transition into instability. A periodic structure of the transition points with external cavity length similar to that discussed in chapter 4 is theoretically predicted [142]. A larger range of feedback fractions are predicted to result in unstable behaviour for PCF [139] and this is found to be influenced by the response time and the interaction depth of the PCM [144,145]. The frequency spacing of the external cavity resonator modes is predicted to be half that of the COF case [139,143] if the conjugation is achieved by non-degenerate four-wave-mixing. The majority of these models apply to instantaneously responding PCMs with zero penetration depth and weak feedback (ie the III→IV transition). No theoretical treatment to date describes the region of strong feedback.

Previous experimental studies on diode lasers with PCF have considered both high power devices (broad-area diode lasers and laser diode arrays) - to be discussed in the next chapter, and narrow-waveguide diode lasers – addressed in the current chapter. PCF into narrow-waveguide diode lasers has been found to induce a multi-mode state indicative of coherence collapse [120,133], to force predominantly multi-mode lasers to operate single-mode [123] or with increased side mode suppression [134], to narrow the lasing linewidth [123,124,127] (below that possible with COF [121]), to provide frequency stabilisation, [127,129] and mode locking [130-132], to reduce turn-on-jitter [277], and to induce a self-frequency scanning of the laser output [125]. These effects have been observed at a number of different feedback levels, as dictated by the phase conjugate efficiency. However, no
systematic investigation of the behaviour of the optical spectrum and output noise (indicating the systems dynamic state) with PCF, or a comparison to the case of COF has been reported.

In the current work the regime of coherence collapse for a nearly single-mode diode laser subject to PCF is experimentally investigated and compared to the same diode laser with plane mirror feedback. In particular, the evolution (with increasing feedback level) of the intensity noise spectrum, the optical frequency spectrum, and the output power versus time, are observed. From these observations, inferences can be made about the system’s high frequency dynamics. In addition, critical feedback levels that result in transitions between stable and unstable regimes are compared for a number of different cavity lengths and for the two cases. The main difference between the two systems (COF and PCF) is found to occur at the IV→V transition. It is found that a state characterised by an intensity noise spectrum consisting of large broad peaks at the external cavity mode spacing and an optical spectrum consisting of the excitation of adjacent solitary diode modes is observed for PCF but not for COF. Also observed at certain feedback levels for PCF is a temporal evolution of the optical frequency spectrum through a number of distinct states, and an LFF state. A number of general characteristics observed are consistent with the current theoretical understanding.

6.2 Generation of phase conjugate waves

6.2.1. The photorefractive effect

There are a number of different methods for generating phase conjugate waves. These include stimulated Brillouin scattering, stimulated Raman scattering, four-wave-mixing in Kerr-like media, and four-wave-mixing in photorefractive material [278]. Photorefractive four-wave-mixing in a suitable crystal medium has been used in the current work because it has the advantage of requiring only low power pump sources to generate relatively high efficiencies, and this can be achieved by self-pumping the crystal.

The photorefractive effect is a nonlinear optical phenomenon whereby the photoconductive and electrooptic properties of a material can lead to modifications of the materials’ refractive index in the presence of nonuniform optical fields. This effect was first reported in LiNbO₃ (lithium niobate) in 1966 [279]. Materials that exhibit this effect rely on photoinduced space-charge fields, which via the linear electrooptic effect modulate the refractive index of the material. The space-charge fields arise from the generation and transportation of charge carriers in the material.
The general principal of the photorefractive effect can be illustrated by considering a photorefractive medium that is illuminated by two incident plane waves of the same frequency. The two waves will interfere in the medium causing an intensity interference pattern that has the distribution function of a grating. This light field, through photoconduction, will cause photoexcitation of electrons from the valence band of the material to the conduction band. The rate of photoexcitation is dependent on the intensity of the radiation field, and hence will vary as the intensity interference grating. Electrons that have been excited into the conduction band, and holes in the valence band, are free to migrate. They will diffuse towards regions of lower intensity and then recombine with greater probability in these regions. This redistribution of charge carriers results in a space-charge field that has the same spatial distribution as the intensity interference pattern.

The space charge field results in a modulation of the refractive index throughout the material due to the linear electrooptic Pockels effect. Because all photorefractive materials are also piezoelectric [280], stress and strain gradients in the material result in a phase shift that occurs between the illuminating intensity interference grating and the resultant refractive index grating [281]. This phase shift has important consequences in that it allows two wave coupling and photorefractive oscillation, which are crucial to the operation of most self-pumped phase conjugate mirrors.

Several distinct categories of materials exhibit photorefractive properties. Photorefractive ferroelectrics, such as LiNbO$_3$, BaTiO$_3$, KNbO$_3$ (potassium niobate), and photorefractive sillenites, such as Bi$_{12}$SiO$_{20}$, Bi$_{12}$GeO$_{20}$, and Bi$_{12}$TiO$_{20}$, are advantageous because they have the strongest electrooptic coefficients leading to the largest refractive index changes with light intensity and hence the highest phase conjugate efficiency. Due to their low carrier mobility, these materials respond very slowly to incident radiation fields, and thus gratings typically take several minutes to build up. Photorefractive semiconductors, such as GaAs, InP, CdTe and CdS, respond very fast to changes in incident light field intensity due to their large carrier mobilities, and crystals are available in good quality and size, particularly at infrared and near infrared wavelengths. However, they generally exhibit low undoped electrooptic effects and hence only low phase conjugate reflectivities are achievable [280]. Methods exist to improve response time and efficiency of phase conjugate crystals, including the application of external electric fields and crystal heating [282,283]. However, the magnitude of these improvements is not large and they complicate the phase conjugate mirror.
6.2.2. Self pumped phase conjugate mirrors

The process of four-wave-mixing in a bulk photorefractive crystal is similar to the process of collinear four-wave-mixing in a semiconductor diode laser, which was described in section 2.4. In the bulk crystal, however, the mixing process is spatial as opposed to temporal. A probe beam and two pump beams are input into the crystal. The probe beam and one of the pump beams interfere in the crystal generating a refractive index grating via the process of photorefraction described in the previous section. The phase conjugate of the probe beam is then generated by scattering of the second pump beam off this grating.

Conventional four-wave-mixing phase conjugate mirrors require high quality externally provided pump beams. These external reference waves generally complicate the structure of such devices- particularly when the PCM is used as part of a resonator. Self pumped phase conjugate mirrors (SPPCM), however, avoid the need for these beams by self-diffracting part of the wave to be conjugated, and by using four-wave-mixing of the incident beam with the self diffracted and retroreflected self-diffracted beam. A number of different configurations of such SPPCM have been demonstrated, which utilise different mechanisms for producing pump waves. These include the linear and semi-linear self-pumped PCM, ring passive PCM, double PCM, and the two-interaction-region passive PCM.

![Figure 6.1: (a) Linear SPPCM, (b) two-interaction-region SPPCM.](image)

The first demonstrated passive (self pumped) phase conjugate mirror was the linear SPPCM, reported in 1982 [284]. The basic layout of the device is shown above in figure 6.1 (a). It consists of a photorefractive crystal that is placed in a linear cavity, ie bounded by two ordinary mirrors. The input of the device is the signal beam 4, which through the process of two beam coupling provides gain for light scattered in the direction of beam 1. This beam is
6.2. Generation of phase conjugate waves

fed back into the crystal from mirrors M1 and M2, being re-amplified in each pass through the crystal. If the gain exceeds loss (mirror loss and crystal absorption), then the counter-propagating oscillations continue until a steady state condition is reached (for beams 1 and 2), which then act as pumping beams for the phase conjugating mirror with an input beam 4. As the physical basis for the build up of the oscillation of the pump beams is through the process of light amplification by two wave mixing then this effect can only occur in devices in which the phase shift between the index grating and interference pattern is non-zero [285].

The two-interaction-region SPPCM or cat mirror (shown schematically in figure 6.1 (b)) was first reported using a crystal of BaTiO3 in 1982 [286]. This device is a compact and very high fidelity SPPCM. It makes use of total-internally reflecting surfaces of the photorefractive crystal as feedback mirrors. It consists of a single photorefractive crystal. Inside the crystal there are two regions of nonlinear interaction: a ring mirror (region C) with a double phase conjugate mirror (region C’) in its feedback loop. Both interaction regions are bounded by the crystal surface that provides feedback through total internal reflection. The two pump beams are thus derived from the incident beam itself inside the crystal. This two interaction region model is but one of several conceptual models that describe the physical processes occurring in such PCMs [278].

This mirror has distinct advantages over other SPPCMs. Although it has a high coupling strength threshold for finite reflectivity output [278], it requires no external optics and is easy to align. The two-interaction-region mirror has been shown to be self-starting in some cases, due to effective seeding by the fanning effect, which results from two beam coupling amplification [278]. In other cases a seeding beam is required in order to bring the oscillating beams intensities above the required threshold value.

6.2.3. Feedback from a semiconductor conjugator

As a comparison to the effects of phase conjugate feedback from a photorefractive phase conjugate mirror it was intended to examine the effects of phase conjugate feedback generated in a semiconductor diode laser (either a broad-area [152,213] or narrow-waveguide [111] device). This would enable the effects of the relative response times of the two different mirrors to be characterised in terms of the output of the system. However, experimental investigation has determined that such an arrangement is not feasible for use as feedback.

The process of phase conjugate generation via four-wave-mixing in a semiconductor laser diode was discussed in section 2.3. It involves injecting a beam from a master diode
laser into the cavity of the slave diode laser, and adjusting the relative powers and frequencies of the slave and master lasers inside the slave diode active layer. To examine feedback effects the optical isolator would be removed and the phase conjugate beam (of the input master laser) would then be coupled back into the master laser. A number of prohibitive difficulties render such an experimental configuration unrealisable.

Firstly, to generate a phase conjugate beam in such a manner, it is desirable that the master laser is tunable. Thus, an external cavity device is typically used. For feedback purposes, both master and slave lasers are required to be individual diode lasers. As the frequency detuning between the two must be on the order of several GHz to achieve a conjugate signal, the master (and slave) lasers must be tuned by current and temperature. It is difficult to find two diode lasers that are tunable in such a method within such a bandwidth. Often many different diode lasers of the same manufacturer must be tested to find a match, and this is an expensive procedure.

Secondly, only a narrow range of detunings and injected (probe) powers will generate a conjugate signal in the slave diode laser [114] (as illustrated in figures 2.7). When the isolation between the two lasers is removed, the feedback into the master laser will necessarily alter the master lasers operating frequency and output power, thus destroying the essential conditions for phase conjugate generation in the slave laser.

The third difficulty arises because the phase conjugate wave generated is frequency shifted from the input probe wave (of the master laser), and the slave laser output contains a component at the slave laser centre frequency and the reflected (amplified) probe frequency, as shown in figure 2.8. The frequency shift alters the system, so that comparisons are not possible with the photorefractive phase conjugate mirror. In addition, the conjugate signal must be isolated from the probe and pump signals. This is not possible through polarisation control as the phase conjugate wave is not a spatial conjugate [112] (as discussed in section 2.3). While frequency control (for example with a static Fabry-Perot interferometer) is a possibility, it significantly complicates the system.

The fourth problem is that the conjugate wave generated in this process is very weak compared with the output of the master laser required to generate the conjugate signal. There is an immediate loss of greater than 80 % due to the coupling efficiency of the slave laser to the injected signal. In addition the phase conjugate power generated is significantly lower than the probe and pump powers. Maximum conjugate efficiencies of <1% have been obtained [111]. Thus, only very low levels of feedback could be examined, which would not be a true comparison to the case of PCF generated in a bulk crystal.
6.3. Experiment

6.3.1. Set-up

![Experimental set-up for PCF](image)

*Figure 6.2. Experimental set-up for PCF. For COF the barium titanate crystal is replaced by a plane mirror.*

The experimental arrangement for the diode laser with phase conjugate feedback is shown in figure 6.2. The solitary diode laser used is the same device as in the previous chapters, ie a quantum-well, index-guided, hi/lo reflection coated, 850 nm, 50 mW device (STC # LT50-03U); which is mounted on a heat sink and temperature controller. The output is collimated (with a Melles Griot GRIN rod lens) and feedback is generated at a distance of 50-1000 mm. Phase conjugate feedback is obtained from an internal reflection geometry self-pumped rhodium-doped (1300 ppm) BaTiO₃ crystal (of dimensions 56 x 62 x 82 mm). The maximum phase-conjugate reflectance achieved is 50%, which is well within the strong feedback regime. The Glan-taylor prism is used to ensure horizontal polarisation (in the same plane as the crystal c-axis). For the diode laser with conventional optical feedback the barium titanate crystal is replaced by a plane mirror of 95% reflectivity. In both cases, an intra-cavity beam splitter is used to pick off some of the intra-cavity power to allow monitoring of the system output and external feedback fraction (defined in the same manner as in chapter 3 equation 3.1), and a variable attenuator is used to control the amount of feedback.

There are a number of experimental observations that can be used to describe the system. Because the system’s dynamics occur on a very fast time scale (sub picoseconds), these cannot be observed directly as a very fast photodiode and oscilloscope or a streak camera is required. The dynamics, however, can be inferred from the output intensity noise spectrum and the optical frequency spectrum. The intensity noise is observed with a fast
(3GHz) photodiode connected to a radio frequency spectrum analyser. The optical frequency spectrum is observed with a 10 and 1000 GHz free-spectral-range Fabry-Perot interferometer and an Optical Spectrum Analyser at resolutions of the external-cavity mode frequency (500 MHz for a 30 cm cavity) and the longitudinal mode spacing of the solitary diode laser (87 GHz). Each of the observations considers the transition from stable single-mode regime III operation, evolution through the unstable regime IV, and the subsequent transition to regime V. As in earlier chapters, the low feedback regimes I and II are not explored, as the stable/unstable behaviour is the object of the investigations.

To ensure the fidelity of the phase conjugate reflection, image restoration experiments have been performed. Similar experiments are described in a number of references [287,288]. They involve placing an image (on a transparency) in the diode laser output beam. A distorting element (some diffuse medium) is then placed in between the transparency and the phase conjugate mirror. If the reflected beam is a true conjugate beam, then the image will be restored in the reflection regardless of the distorting medium, as the beam retraces its original path back through the medium. If the reflected beam is not a conjugate of the input beam, for example if it is a stray or spurious reflection, then the image will be doubly aberrated by its second path through the distorting medium.

The response time and efficiency of the phase conjugate mirror can be determined by the time it takes to build up a grating in the crystal. The response time is found to vary with the angle of incidence of the probe beam on the crystal c axis; larger angles result in a slower response time (as observed in reference [289]). In general, the build up time is also influenced by the position of the probe beam on the crystal surface (with respect to the edge of the crystal) and the probe power. Different positions are found to generate different dynamic states of the output conjugate efficiency [290]. Pulsing, semi-periodic, chaotic, and stable states have all been observed according to the incident beam position. For stable output the time to build up a maximum phase conjugate efficiency is 200-300 seconds.

6.3.2. Coupling efficiency

While several methods have been applied to estimate the coupling efficiency from system measurables for the case of COF [43,51,241] (as used in chapter 3), and for optical injection (as used in chapter 5), no such method has been reported for the case of PCF. Theoretical models typically consider the coupling coefficient for PCF to be unity [140,146] due to the temporal phase reversing nature of the feedback.
The coupling efficiency was estimated in chapter 3, for the case of COF, and for injection locking in chapter 5. For COF, the value was determined from fits of slope efficiency and threshold current as a function of feedback power (equations 2.24, 2.25). This method, however, cannot be used to determine the coupling efficiency $\eta_{pcf}$ when the feedback is produced by a phase conjugate mirror. This is because the phase conjugate efficiency is not a linear function of the pumping power. It is found that the reflected power is constant over a wide range of incident powers, and thus the efficiency actually decreases with an increase in power. Since the reflected feedback power does not increase linearly with current, the slope efficiency and threshold are not measurable. However, equations (2.24) and (2.25) can be combined in order to predict the output power at a given current and feedback ratio, as a function of the feedback efficiency; similar to the model describing output power variations with external mirror tilt. The output power may be expressed as a function of the external feedback fraction or the coupling coefficient.

$$P_{out}(R_{ext}, \eta_c) = \eta_{ex}(R_{ext}, \eta_c) \left[ I - \eta_{th}(R_{ext}, \eta_c) \right]$$  \hspace{1cm} (6.1)

**Figure 6.3.** Prediction of variation of output power with coupling coefficient (solid curve) from equation (6.1) for a fixed feedback ratio of 0.20 in (a), 0.20 in (b), 0.05 in (c) and 0.10 in (d), and injection current of 50 mA in (a), 55 mA in (b), 55 mA in (c), and 60 mA in (d). The dashed line represents the COF output power for this feedback ratio and current. The dotted line represents the power for PCF.
Although this equation (6.1) is based on assumptions that only apply for weak feedback, the agreement between theory and the experiment in chapter 3, regarding the change in output power with asymmetric feedback, suggests that this model qualitatively describes the moderately strong feedback case. Secondly, the feedback fractions used to calculate the phase conjugate coupling efficiency are lower than 0.2. When higher feedback fractions are used, the experimental observations deviate from the theoretical agreement reached at low feedback.

Figure 6.3 shows the output power as a function of the coupling coefficient for a fixed feedback ratio and injection current predicted by equation 6.1. The power is found to decrease with an increase in the coupling efficiency (or feedback ratio) at currents above the solitary diode threshold. This is because the slope efficiency and the threshold injection current are both decreasing, hence at very low currents the largest $\eta_{pcf}$ (or $R_{ext}$) will have higher power, but as current is increased the largest $\eta_{pcf}$ (or $R_{ext}$) will have a lower power. Also shown in the figure are lines at the experimental output power ($P_{out}$) at this current and feedback ratio, for both COF and PCF.

For COF the output power corresponds to a coupling efficiency of $\eta_c \sim 0.28$, this agrees with the earlier determination (section 3.2.2). For the diode laser with PCF, the output power is significantly lower for the same injection current and feedback level. The coupling efficiency is determined from fits of the experimentally observed output power to the theoretically predicted output power versus coupling efficiency, for a number of different injection currents and feedback ratios. For low feedback levels (less than 20 %) the coupling efficiency is determined to be $\eta_{pcf} = 0.7 \pm 0.1$.

This value is in agreement with that determined from examining the output power as a function of external feedback fraction at a fixed injection current. Experimental data and the theoretical prediction (equation 6.1) is shown in figure 6.4, below, for both COF and PCF, at injection currents of 40 mA (a) and 70 mA (b). At low injection currents (a) the output power is always increased with an increase in coupling efficiency. At higher injection currents, however, the output power decreases with feedback fraction and coupling efficiency. The theoretical lines in the figure represent coupling efficiencies of 0.7 for PCF and 0.28 for COF. The deviation of the theoretical model from the experimental observations for high feedback is shown in the figure. For external feedback fractions below 0.2 there is good quantitative agreement. As the external feedback fraction is increased above this value, the predicted output power disagrees with the experimental power. More experimental data points are required to ascertain if the disagreement is systematic.
Figure 6.4. Output power versus external feedback fraction for conventional optical feedback and phase conjugate feedback. The injection current is 40 mA in (a) and 70 mA in (b). Solid lines are the theoretical fit to the experimental data points.

This result has important implications for strong-feedback external-cavity laser systems, which would benefit from the significant increase in coupling efficiency by using phase conjugate feedback rather than conventional mirror feedback. It also allows an improvement in the accuracy of theoretical models describing the effects of phase conjugate feedback on diode laser operation.

### 6.4. Experimental observations

#### 6.4.1. Evolution of the intensity noise spectrum with feedback

The intensity noise spectrum is the autocorrelation function of the Fourier transform of the output power over time. Previous theoretical analyses has demonstrated a correspondence of the specific features of the intensity noise spectrum with the dynamic state of the laser output. Figure 6.5 illustrates this correspondence. If the output power is constant in time (a) then the noise spectrum is flat. If the output power is oscillating at some frequency then the noise spectrum comprises a peak at this frequency; the predicted initial bifurcation is shown, ie oscillation at the relaxation oscillation frequency of the solitary diode laser (b). If the output power is oscillating in a higher ordered dynamic cycle (c), then the noise spectrum comprises peaks at the competing frequencies present; in this case the external cavity frequencies are excited in addition to the relaxation oscillation. For an output power that is chaotic in time,
the noise spectrum is characterised as shown in (d). For an output in the state of low frequency fluctuations, the intensity noise spectrum comprises significant components at low frequencies (e).

![Diagram](image)

**Figure 6.5.** Theoretical prediction of the correspondence of the output power versus time (left column) with intensity noise spectrum (right column), for five different dynamic states. After [40,41].

The experimentally observed evolution of the output intensity-noise spectrum for both COF and PCF is shown in figure 6.6, for two different cavity lengths. For all figures the lowest feedback level shown (spectra a) represents the system operating in a stable single-
mode (regime III). In this state the noise level is below the dark noise of the detection system (which is shown). This indicates an output power that is constant over time. For the case of COF (i,ii), if the feedback level is increased the noise spectrum undergoes a transition into a state (b) where the external cavity mode frequencies have been excited. These are spaced by 500 MHz and 330 MHz; representing external cavity lengths of 300 mm (i) and 450 mm (ii) respectively.

Previous experimental and theoretical investigations [41,76,146] have shown that the initial bifurcation from steady state behaviour is commonly to a periodic state of oscillation at the relaxation oscillation frequency. This state would manifest itself on the optical frequency spectrum as a solitary peak at the relaxation oscillation frequency (as shown in figure 6.5 (b)). This is not observed due to the current experimental frequency range and resolution and possibly because the diode laser used has a highly damped relaxation oscillation. The observed initial transition from the stable low-noise state is to a state with excited external-cavity mode frequencies. This represents a modulation of the relaxation oscillation by the external-cavity mode frequency; ie some ordered periodic solution, with a temporal output power similar to that shown in figure 6.5 (c). As the feedback is further increased the noise peaks at the external-cavity mode spacing broaden and decrease in magnitude, and a number of smaller peaks of irregular spacing are observable (spectra e,f,g). These spectra imply bifurcation into higher order dynamics, and finally chaos; where the smaller peaks represent harmonic and entangled frequencies of the external cavity modes, the solitary diode longitudinal modes and the solitary diode’s relaxation oscillation. It is unclear at which exact feedback fraction the system is operating chaotically, although the noise spectrum that appear in (f) and (g) are characteristic of chaotic output as theoretically predicted [41,140,141]; ie compare to figure 6.5 (d).

When the plane mirror is replaced with a PCM the noise spectrum evolves somewhat differently. This is shown in figure 6.6 (iii, and iv), for cavity lengths of 300 mm and 450 mm respectively. It can be seen that the resonant noise frequencies occur at the same excited mode frequencies (c/2L) as for COF for both cavity lengths; this is found to be the case for all other cavity lengths examined (50-1000 mm). The evolution of the noise spectrum (for PCF) also shows similar characteristics for all cavity lengths. The initial excitation of the external cavity modes, which occurs at the first transition into the coherence collapse regime (spectrum b) from the low feedback regime, is common to observations of the COF system. However, the external-cavity mode resonances do not reach the same magnitude and are much broader. There are two possible reasons for this difference. Firstly, it may be that the PCF system
bifurcates into higher order dynamics more quickly than the COF system and the initial bifurcations occur on a finer resolution of feedback level than experimentally observable. Secondly, it may be that total internal reflection geometry PCM introduces an uncertainty in the external cavity length, due to the dynamically forming grating within the crystal relying on beam fanning effects. This may cause a loss of constraint on the system’s lasing frequency.

Figure 6.6. Intensity noise spectra for increasing COF level (i, ii), and PCF level (iii, iv). The external cavity length is 300 mm in (i) and (iii), 450 mm in (ii) and (iv). The COF external feedback fractions (i,ii) from a-h are 0.0015, 0.0020, 0.0050, 0.0075, 0.01, 0.015, 0.025, 0.05 respectively. The PCF external feedback fractions from a-h are 0.0004, 0.0006, 0.0015, 0.005, 0.01, 0.05, 0.10, 0.25 respectively. All spectra are plotted on identical vertical scales that are shifted vertically for clarity.

Unlike the simple transition from broadband chaos into single-mode behaviour which is observed for COF, the transition into regime V (h) for PCF is preceded by a significant excitation of the noise around the external cavity mode frequencies (e, f, g). There is still a large number of closely spaced smaller peaks at these feedback levels. This indicates that the IV→V transition for PCF may involve a series of bifurcations into stability, or some other
higher order dynamic state. There is also a significant increase in the noise at low frequencies, which again does not occur for COF. This may be due to mode partition noise, or low frequency fluctuations.

6.4.2. Evolution of the optical frequency spectrum with feedback

![Optical frequency spectra](image)

Figure 6.7. Optical frequency spectra for increasing feedback level. COF is shown in (i) with external feedback fractions from a-g of 0.0015, 0.0020, 0.0070, 0.01, 0.015, 0.025, 0.05 respectively. PCF is shown in (ii) with external feedback fractions from a-g of 0.0004, 0.0006, 0.005, 0.01, 0.05, 0.10, 0.25 respectively. Injection current is 50 mA. All spectra are plotted on identical vertical scales that are shifted vertically and horizontally for clarity.

The optical frequency spectrum for a range of feedback fractions has been observed for the diode laser subject to COF and is shown in figure 6.7 (i). The free spectral range is 1000 GHz, which allows the mode structure of the solitary diode laser (longitudinal modes
spaced by 87 GHz) to be resolved. Spectrum (a) corresponds to a low feedback level which results in stable single-mode behaviour (regime III), with side mode suppression (not resolvable at the given scale) of greater than -30 dB. Increasing the feedback results in an abrupt transition to a multi-mode state (b), which corresponds to an excitation of the external cavity mode frequencies in the noise spectrum (as shown in figure 6.6 i (b)). Further increase in feedback results in an increase in the number and magnitude of the solitary diode laser modes (c-f), until at a feedback level of $R_{ext} = 0.05$ there is an abrupt transition to stable single-mode regime V operation (g).

**Figure 6.8.** Optical frequency spectra for increasing feedback level. COF is shown in (i) with external feedback fractions from a-f of 0.0015, 0.0020, 0.007, 0.015, 0.025, 0.05 respectively. PCF is shown in (ii) with feedback fraction of 0.0004, 0.0006, 0.005, 0.05, 0.22, and 0.25 respectively. The FSR is approximately 10 GHz. The external cavity length is 300 mm. Injection current is 50 mA. All spectra are plotted on identical vertical scales that are shifted vertically for clarity.

At low feedback levels, the optical spectrum evolves similarly for the case of PCF (figure 6.7 (ii) b, c, d). However, at feedback levels $R_{ext} > 0.05$ (e, f) a new state is observed. This state comprises lasing on two adjacent solitary diode laser modes, and corresponds to the noise spectra that comprises broad peaks at the external-cavity mode spacing.
(figure 6.6 (iii) f and g). Such an observed spectrum may represent either the system lasing simultaneously on two (adjacent) modes, or rapid mode hopping between the two, similar to the regime II mode hopping state observed at very low feedback levels for COF. Although the presence of significant noise at low frequencies indicates that the system is mode hopping, ie as due to mode partition noise, it has been experimentally determined that mode hopping does not occur at frequencies slower than 15 MHz.

If the optical frequency is examined at a higher resolution, that of the external cavity modes (FSR 10 GHz), further differences are observed between the two systems. Figure 6.8 (i) shows the evolution with feedback power for COF; which exhibits a stable single-mode (a) transition into a state of excited external cavity modes (b, c). With increased feedback, the output evolves into a broadband multi-mode spectrum indicative of chaos (d, e), before switching back to single-mode behaviour (f). Figure 6.8 (ii) for PCF shows the same evolution, although the broadband chaotic spectra (c,d) develop more rapidly, and the bandwidth is higher than that for COF. However, there is also a small region of feedback fractions close to the IV→V transition (e), which show a temporal evolution of the output state with fixed feedback fraction.

![Optical frequency spectra for PCF at a fixed external feedback fraction](image)

Figure 6.9: Optical frequency spectra for PCF at a fixed external feedback fraction $R_{ext} \approx 0.22$. The output evolves over time through the sequence of distinct states shown. The solitary diode injection current is 50 mA. All spectra are plotted on identical vertical scales that are shifted vertically for clarity.
This is shown in more detail in figure 6.9. The output is observed to cycle through a number of distinct states over the time interval of 0.5-1 seconds. It generally starts in a chaotic multi-mode state (a) then switches to a state with excited external cavity modes (b) which increase in number (c,d) before a transition to a state of lasing on the fundamental mode with a series of sidemodes (e,f) spaced by approximately 2-3 GHz. The separation between the central peak and the side modes is found to increase linearly with the square root of the current above threshold, as shown in figure 6.10, below. This indicates that this state is an excitation of the solitary diode’s relaxation frequency, similar to that observed in collinear non-degenerate-four-wave-mixing [86] or injection locking [102] in semiconductor diode lasers. This evolution of the output state with time is due to the self-induced frequency scanning of the phase conjugate feedback, which occurs at these feedback fractions. Such scanning has been previously observed in a similar geometry PCM [125], although the phase conjugate signal is isolated in that case and therefore the multi-mode dynamics have not been observed. This state occurs because the feedback is now detuned from the diode’s fundamental lasing frequency and the detuning is changing over time.

![Figure 6.10: Peak separation versus the square root of the current above threshold, for the output spectrum as appears in figure 6.9 (e and f).](image)

6.4.3. Feedback regimes

The feedback levels at which transitions between stable and unstable output states occur for PCF and COF as a function of injection current are shown in figure 6.11. The external feedback fraction at which the III→IV transition occurs for both COF and PCF
shows a similar functionality, but the PCF transition occurs at lower feedback fractions. When the difference in the coupling efficiencies ($\eta_c$ and $\eta_{pcf}$) is taken into account by examining the internal feedback fraction (defined as $\eta_cR_{ext}$ or $\eta_{pcf}R_{ext}$) then the III→IV transition is found to occur at similar values. This indicates that the same levels of feedback coupled into the diode laser active layer induce similar output states regardless of the type of feedback (COF or PCF), provided that the feedback is weak. For stronger feedback there is no correspondence between the behaviours observed. The IV→V transition for COF has a similar functionality with respect to the injection current as was observed in chapter 4. For PCF the IV→V transition occurs independent of diode laser injection current, and the effect of the difference in coupling efficiency is to increase the discrepancy between the two systems. Thus, for higher feedback fractions there is some distinction between the two feedback fields inside the laser cavity that does not depend only on the relative feedback strengths, and does not occur for low feedback levels.

![Figure 6.11](image)

**Figure 6.11.** External feedback fractions (a) and internal feedback fractions (b) at which transitions between stable and unstable regimes occur as a function of injection current. Triangles represent the III→IV transition, circles represent the IV→V transition. Solid points represent COF, open points are PCF. The external cavity length is ~300 mm.

In chapter 4, the dependence of the transition points on the external cavity length was examined for COF. It was found that the transition into coherence collapse is suppressed for cavity lengths less than ~80 mm, as the feedback fraction of the III→IV transition point increases with a decrease in the external cavity length. This behaviour is compared to that of the diode laser with PCF in figure 6.12. For PCF the transition points remain approximately
constant over the full range of experimentally investigated external cavity lengths (50 - 1000 mm). The III→IV transition is found to occur at an external feedback fraction of approximately 0.005 and the IV→V transition occurs at approximately 0.20 regardless of cavity length.

Figure 6.12. The feedback fractions at which transitions between stable and unstable output states occur for PCF (solid circles) and COF (open triangles). The points mark transitions from stable single-mode regime III into coherence collapse regime IV, and from coherence collapse regime IV into stable single-mode regime V. Injection current is 55 mA.

Figure 6.13. External feedback fraction of the IV→V transition as a function of the PCM crystal temperature. Diode laser injection current is 55 mA.
The effect of the response time of the phase conjugate mirror can be altered by increasing the crystal temperature [283]. This has been found to influence the transition points for the IV→V transition. As shown in figure 6.13, when the crystal is heated (increasing the response time) the external feedback fraction of the IV→V transition point is reduced. The crystal temperature has no effect on the III→IV transition.

Figure 6.14. Low frequency fluctuations induced by PCF, near the IV→V transition. External feedback fractions are 0.20 in (a and b), and 0.15 in (c and d). Solitary diode injection current is 38 mA in (a,b,c) and 52 in (d). External cavity length is ~300 mm.

A state of low frequency fluctuation (LFF) for PCF has also been observed at certain injection currents and feedback fractions. This state has not previously been observed, to the authors’ knowledge, for PCF. The LFF state for several different system parameters is shown in figure 6.14. The frequency of the power drop-outs is in the range 10-500 MHz, which is dependent on the external cavity length and the exact value of the feedback. The system parameters also effect the characteristics of the LFF state, and power jump-ups are observed at certain injection currents. Similar behaviour has been observed in the literature for COF systems. There are no observable differences in the characteristics of the LFF state between the COF and PCF systems.

The LFF state is found to occur at the boundary between regimes III and IV for low injection currents (close to threshold), and at the boundary between regimes IV and V for
higher injection currents (~\(2I_{th}^{dL}\)). A full analysis of the range of feedback fractions and injection currents at which the LFF is observed has not been carried out. The LFF state for COF is accompanied by a multi-mode optical frequency spectrum (at the external cavity and solitary diode longitudinal mode frequencies) of similar characteristics to figure 6.7 (i) spectrum f, and figure 6.8 (i) spectrum e (as observed in ref [50]). The intensity noise spectrum comprises strong peaks at the external cavity mode spacing and at low frequencies (similar to figure 6.6 (i) spectra b and c). For PCF the optical frequency spectrum of the LFF state is also multi-mode but as it occurs close to the IV→V boundary it consists of two (adjacent) mode oscillation as in figure 6.7 (ii) spectra e and f. The LFF state occurs for a small range of feedback fractions that are lower than the induced temporally evolving state as depicted in figure 6.9. The LFF state for PCF also has significant noise at low frequencies, corresponding to spectra g of figure 6.7 (iii) and (iv).

6.5. Comparison with theory

Interpreting the results in terms of existing theories is difficult because there are currently no theoretical models that are entirely appropriate to the present experimental parameters. Of primary importance is that models based upon the Lang-Kobayashi rate equations use approximations which are only applicable for low feedback levels, and thus only the experimental and theoretical data for the III→IV transition is comparable. The new results have been observed at the IV→V transition, and there is no published theoretical research on PCF for such high optical feedback levels. Secondly the present experiment involves a PCM with a finite response time and penetration depth, and although there has been some theory to account for this, the majority of published work considers an instantaneous response. Some models also consider the PCF with detuning; ie not for an internal geometry self-pumped mirror, as is the case in the present work, but for a non-degenerate four-wave-mixing geometry.

Qualitative agreement between theory and the current experimental observations exists in a number of areas. Although the chaotic evolution with feedback is very much parameter driven, ie small changes in the many system variables result in different dynamic features, the general characteristics of PCF induced dynamics, which are distinct from those associated with COF, are consistent with the current data. A difference between the length dependence of PCF and COF is predicted [142] (although for a instantaneous response time PCM), and a
6.5. Comparison with theory

change in this PCF length dependence with response time is predicted in ref [144] (although for detuned PCF). A change in system stability with response time has also been predicted [139,144,145] and while the theory considered quite large differences in response time, the experiments indicate that even small increases lead to modified stability conditions.

The results of the experiments reported here indicate the directions and the important parameters that need to be included for a full theoretical description of diode lasers with PCF. These are multiple external cavity round trips to account for high levels of feedback, a variable time response of the phase conjugate mirror, and the possibility of an ill-defined external cavity length when a two-interaction-region PCM is used. Further experimental results are also needed for a full description of these systems. Areas of study should include repetition of the above experiments using a phase conjugate mirror with a faster response time, a phase conjugate mirror using non-degenerate four-wave-mixing (rather than self-pumped), and a different type of solitary diode laser. The observation of a temporal evolution of the output state observed near the IV-V transition for PCF is probably too complex to treat theoretically. It relies on the phenomenon of self-induced frequency scanning which is not entirely understood, is difficult to fully characterise, and occurs at strong feedback levels. All of these represent very difficult theoretical problems.

The observation of the external cavity mode spacing, $c/2L$, as the dominant frequency appearing in the relative intensity noise and optical spectra, for both COF and PCF, as the transition to unstable operation occurs is worthy of further discussion. Several authors have predicted that the observed dominant frequency is $c/4L$ for PCF compared to $c/2L$ for COF in theoretical studies [139]. These studies have been for non-degenerate four wave mixing (NDFWM) and in turn refer to earlier work [291], which demonstrated that there is no stable mode for a single round trip in the non-degenerate case. However for the case of degenerate FWM, which is relevant for the present experiments, ref [291] shows that there are a large range of possible stable modes for both single and double roundtrips, with the only constraint being that the mode will have a radius of curvature that matches the radius of curvature of the real mirror of the two mirror resonator (the second mirror being the PCM). The mode that will actually lase will be the one which uses the available gain most efficiently taking into account any real or effective aperturing arising from, for example, the spatial extent of the pump beams [291]. In the laser system studied here, the “real” mirror is in fact the laser diode end facet, or indeed, the laser diode waveguide. The experimental results demonstrate that the mode that uses the gain most efficiently in this system, with both PCF and COF, is the single roundtrip mode. Some previous experiments of PCF in laser diodes [127,136] have observed
c/4L modes when utilising spectrally degenerate FWM and have taken this observation of c/4L modes as proof that phase conjugate feedback is being generated. An independent check of the phase conjugate nature of the feedback has been carried out in this study following the method of [287]. The results of all experimental studies of PCF in laser diodes to date [127,136, this work] suggest the c/2L modes will be seen when the PCF is both spectrally and spatially degenerate and the c/4L modes are seen when the PCF is spectrally degenerate but spatially non-degenerate and vice-versa.

6.6. Summary

From the point of view of applications of phase conjugate feedback, of primary importance is the feedback fractions at which transitions between stable and unstable output states occur. The results presented in this chapter indicate that although significantly more light is coupled into the laser diode for PCF, there is a larger range of feedback fractions causing instability. Thus, there is a more stringent requirement on the level of feedback that will produce stable single-mode output. Also to be avoided in practical applications is the temporal instability associated with the self-induced frequency scanning of the photorefractive index grating. Ideally, the feedback from the PCM should be made as high as possible (greater than 50%). This introduces difficulties due to efficiencies of bulk photorefractive crystals, which are not consistently available at such high efficiencies, and restricts the use of semiconductor phase conjugators, which operate with much lower efficiencies.

The experimental results presented in this chapter agree qualitatively in some areas with theoretical predictions from the literature. As in previous chapters the results indicate that quantitative agreement is difficult to achieve because of imprecisely known internal parameters of the solitary diode laser.
Chapter Seven: Broad-Area Diode Lasers

7.1. Introduction

Increasing the width of the active layer, thereby providing a larger gain volume, can substantially increase the output power of a diode laser. Several Watts (cw) is available from such a device, which is known as a broad-area diode laser. Typical active layer widths are ~100 µm, compared to narrow-waveguide active layer widths of 2-10 µm. This higher power is achieved, however, at the expense of transverse mode selectivity. As the active layer is larger it supports multiple transverse modes, and multiple longitudinal modes. The spatial and spectral quality of the output is thus poor. Nonlinear effects, such as self-focussing, can further deteriorate the output profile. Spatially, the output is highly astigmatic and operates with several intensity maxima along the plane of the junction stipe. Spectrally, these lasers are typically multi-mode with effective linewidths of ~500 GHz.

Various methods have been proposed and used to improve the spatial and or spectral output of broad-area diode lasers. These include the use of optical feedback [292-298], optical injection [299], phase conjugate feedback [150,151] and phase conjugate injection [215,216]. Injection with a narrow linewidth single-frequency source has been shown to generate single-frequency and single spatial mode operation [299]. Single-frequency operation has been demonstrated with frequency selective feedback, either from a refractive index grating [293,294] or a plane mirror with an intracavity etalon [292,297]. Phase conjugation has been used with broad-area diode lasers primarily for coupling, typically using double pumped phase conjugate mirrors for injection locking of a broad-area diode laser by a single-mode diode laser [215,216]. Phase conjugate feedback has also been used to generate either single spatial and single spectral mode output from a broad-area laser [150,151].

In the current work the operation of a broad-area diode laser with conventional optical feedback is examined and compared to the case of phase conjugate feedback. In particular the optical frequency spectrum, at resolutions of the longitudinal mode spacing of the broad-area diode laser and the external cavity mode spacing, and the intensity noise spectrum are observed with increasing levels of feedback. It is found that the broad-area diode laser with COF does
not operate on a single-frequency for any value of the feedback, but operates on a distinct multi-mode state indicative of coherence collapse. The diode laser with PCF is forced to operate on a single-mode of the broad-area diode laser, as previously observed, but this mode comprises multiple peaks at the external cavity mode spacing. The transition points between unstable and stable operating regimes are also examined, and compared to observations with the narrow-waveguide diode laser made in the previous chapter.

### 7.2. Experiment

#### 7.2.1. Set-up

The experimental apparatus is shown in figure 7.1 for (a) COF and (b) PCF. The diode laser is a 200 mW, 800 nm broad-area diode laser (Sony #302B). The output is collimated with a GRIN rod lens. An intracavity beamsplitter is used to monitor the output and feedback.
powers, and a variable attenuator is used to control the amount of feedback. The external cavity length is ~300 mm.

For conventional optical feedback the reflection from a plane mirror ($R_{\text{mirror}} = 0.90$) is focussed by an intracavity convex lens (of focal length ~ 150 mm) onto the diode laser front facet. This lens is used due to the poor output spatial mode of the broad-area diode laser. It is highly divergent in the horizontal plane (even after collimation) and thus with no focussing optics very little feedback power can be coupled back into the diode laser.

In order to achieve an efficient phase conjugate generation, the diode laser must be polarised in a direction perpendicular to the crystal c-axis. Additionally, the spatial coherence of the laser output must be as high as possible in this direction. As the output of the broad-area diode laser is highly divergent, and shows low spatial coherence in the horizontal direction, the diode laser is mounted on its side. The half wave plate is used to rotate the polarisation to coincide with the highest spatial coherence and the largest crystal dimensions with respect to the c-axis (ie horizontal). The maximum phase conjugate reflectance achieved in this way is ~8 %. This is significantly lower than that achieved with the same crystal pumped by the narrow-waveguide device (50 %), indicating the importance of a good spatial beam profile for efficiency phase conjugation.

Output diagnostics are, as in previous chapters, a 1000 and 10 GHz FSR Fabry-Perot interferometer, a radio frequency spectrum analyser with a fast photodiode, an optical frequency spectrum analyser, and a power meter.

### 7.2.2. Coupling efficiency

Using the same techniques as for the narrow-waveguide diode laser (section 3.2.2), the coupling efficiency for conventional optical feedback is estimated for the broad-area diode laser. Experimental data for slope efficiency and threshold injection current versus external feedback fraction and the best fits from equations 2.24 and 2.25, is shown in figure 7.2, below. Although the threshold injection current of the solitary diode laser is reduced by a magnitude that is to be expected by the mirror and lens feedback (~25%), the reduction in the slope efficiency is much lower than expected. It changes by less than 5%, compared with the slope efficiency of a narrow-waveguide diode laser, which was reduced by ~30% by the application of COF (figure 3.4).

From this method the coupling efficiency for the broad-area diode laser with lens and mirror feedback is estimated to be $\eta_c = 0.12 \pm 0.06$. Other parameters are determined to
be $\alpha_{int} = 13000 \pm 1000 \text{ cm}^{-1}$, and $\eta_{int} = 0.55 \pm 0.15$ (see appendix A for values of other variables). The coupling efficiency for the broad-area diode laser is significantly lower than that for the narrow-waveguide STC diode laser with COF ($\eta_c = 0.28$), and the narrow-waveguide SDL diode laser with COF ($\eta_c = 0.18$). This is as expected because of the poor output beam profile of the broad-area laser. It is, however, similar to the value determined for the coupling efficiency of the narrow-waveguide STC diode laser with an injected optical source ($\eta_{inj} = 0.12$).

![Figure 7.2](image)

Figure 7.2. Slope efficiency and threshold current versus the external feedback fraction, for the broad-area diode laser with conventional optical (mirror plus lens) feedback. The theoretical predictions (solid lines) are shown fit to the experimental data points.

For the case of phase conjugate feedback, the coupling coefficient is determined by a similar method to that used in the previous chapter. The output power versus external feedback fraction is plotted for both COF and PCF in figure 7.3. Experimental data and the best fits (from equation 6.1) are shown. Unlike the case of a narrow-waveguide diode laser, the output power for phase conjugate feedback is significantly increased relative to the COF power at the same external feedback fraction. This is due to the small relative decrease in slope efficiency with respect to the solitary diode laser value, compared with the large decrease in threshold injection current.

The phase conjugate coupling efficiency is determined in this way to be $\eta_{pca} = 0.5 \pm 0.1$. Once again this value agrees with the expectation that the feedback field from a phase conjugate mirror is coupled much more efficiently than the feedback field from a plane mirror (and lens). However, this demonstrates that there is still significant loss
for a phase conjugate reflection (half the output power), and that more efficient means, such as better mode matching between the two lasers is essential for better performance.

Figure 7.3. Output power versus external feedback fraction for phase conjugate and conventional optical feedback. The solid lines are theoretical fits to the experimental data points (triangles). The diode laser injection current is 250 mA.

7.3. Spectral characteristics versus feedback

Similar to the experiment performed in chapter 6, the evolution of the optical frequency spectrum (at resolutions of the external cavity mode frequency and the diode laser longitudinal mode frequency), and the intensity noise spectrum, with increasing levels of feedback has been observed for the broad-area diode laser with mirror feedback and phase conjugate feedback. These observations are shown in figures 7.4 (for COF) and figure 7.5 (for PCF).

The broad-area diode laser with no feedback operates on a number of longitudinal modes simultaneously, and has a complex mode structure at the external cavity mode frequency (which is just an arbitrary low frequency without feedback). When (conventional optical) feedback is introduced, the optical spectrum develops a more complicated mode structure at the longitudinal mode spacing of the solitary diode laser, and also at the external cavity mode frequencies. As the feedback is increased the optical spectrum rapidly develops into a very broadband multi-mode state; with multiple modes evident at both the external
Chapter Seven: Broad-Area Diode Lasers

Figure 7.4. Optical frequency spectrum at resolutions of the external cavity mode spacing (first column) and the longitudinal mode spacing of the solitary diode laser (middle column), and the intensity noise spectrum (right column) for various levels of the external feedback fraction (as indicated on the left of the figure), for the broad-area diode laser with conventional optical feedback. Diode laser injection current is 250 mA.

cavity and solitary diode longitudinal frequencies. Such spectra have similar characteristics to the unstable state observed in the SDL laser diodes with on axis feedback (in chapter 3); ie it is not characteristic of coherence collapse in a narrow-waveguide laser. The intensity noise spectrum is observed to evolve with feedback very differently than the narrow-waveguide devices examined in the previous chapter. Low feedback levels excite broad peaks at the
external cavity mode frequencies, which develop into very narrow band peaks (of high noise intensity) for high feedback levels. This is opposite to the narrow-waveguide case (cf figure 6.6). No amount of feedback is observed to induce a stable single-mode operation (low noise) at either resolution. Feedback fractions as high as 80% have been examined. A state of low frequency fluctuations has also been observed for low injection currents (close to the solitary diode threshold) and high feedback fractions.

<table>
<thead>
<tr>
<th>External feedback fraction</th>
<th>Optical frequency spectrum</th>
<th>Intensity noise spectrum</th>
</tr>
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<tbody>
<tr>
<td>0.060</td>
<td></td>
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<tr>
<td>0.032</td>
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<td>0.010</td>
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Figure 7.5. Optical frequency spectrum at resolutions of the external cavity mode spacing (first column) and the longitudinal mode spacing of the solitary diode laser (middle column), and intensity noise spectrum (right column) for various levels of the external feedback fraction (as indicated on the left of the figure), for the broad-area diode laser with phase conjugate feedback. Diode laser injection current is 250 mA.
The system develops differently with phase conjugate feedback, as shown in figure 7.5, above. Low feedback levels cause oscillation on several of the diode laser’s longitudinal modes. As the feedback is increased, a critical level is reached, above which the system is seen to operate on a single-mode of the solitary diode laser. However, the evolution with feedback of both the intensity noise spectrum and the optical frequency spectrum at a resolution of the external cavity mode frequencies is similar to that observed for COF, i.e., moderate feedback strength results in very strong narrow noise peaks at external cavity frequencies and oscillation on multiple external cavity modes. Thus, the phase conjugate feedback does provide some linewidth narrowing and suppression of side modes, unlike COF, but the external cavity modes are not suppressed at the maximum phase conjugate reflectance achieved. Such a unique state has not previously been observed in any other feedback or injection configurations throughout this work. Again, significant low frequency noise indicates an LFF state for strong feedback and low currents.

### 7.4. Feedback regimes

The feedback fractions at which transitions between the various output states have been recorded as a function of the solitary diode laser injection current. The broad-area diode laser is observed to behave somewhat differently to the narrow-waveguide devices used previously (chapters 4 and 6). Figure 7.6 (a) shows the external feedback fraction of the transition into instability for both PCF and COF as a function of injection current. This is similar to the regime III \( \rightarrow \) IV transition observed in narrow-waveguide diode lasers. For the broad-area diode laser, however, there is no stable single-mode regime III, instead, the diode laser is stable multi-mode. For very low feedback there is little effect on the output characteristics (frequency and noise spectrum) as shown in figures 7.4 and 7.5. As the feedback is increased, there is an abrupt transition into the state shown for COF \( R_{\text{ext}} = 0.058 \), and PCF \( R_{\text{ext}} = 0.022 \), which has characteristics of a dynamically unstable output power.

As shown in figure 7.6, the transition into this unstable state occurs for low external feedback fractions (< 0.02) at injection currents above ~300 mA \( (2 I_{\text{th}} \, dl) \). As the injection current is decreased the external feedback fraction required to cause the instability rapidly increases. This dependence of the transition point on the injection current is opposite to that observed in previous chapters for the injection current dependence of the regime III \( \rightarrow \) IV transition. In figures 4.9, 4.10, and 6.11, the III \( \rightarrow \) IV transition increases with an increase in
7.4. Feedback regimes

Injection current. Thus, the instability induced in the broad-area diode laser with feedback (from either COF or PCF) shows distinctions from the instability induced in a narrow-waveguide laser with feedback. The mechanisms responsible for the differences between the feedback behaviour for the two types of diode laser probably arise from the support of multiple spectral and spatial modes in the broad-area device. Theoretical modelling of broad-area diode lasers subject to feedback has not been reported in the literature, as the majority of models capable of predicting feedback behaviour in narrow-waveguide devices are not appropriate to multiple spectral modes and higher order transverse modes. The extension of existing multi-spectral and spatial mode models to the examination of broad-area diode lasers with feedback is required to explain the experimental observations reported.

![Figure 7.6. (a) External feedback fraction, and (b) internal feedback fraction, at which transition into instability occurs as a function of injection current.](image)

The transition into instability in the broad-area diode laser with COF occurs at higher feedback fractions than for PCF. The internal feedback fraction, defined (as in chapter 4) as the external feedback fraction multiplied by the coupling efficiency, of the transition is plotted against injection current in figure 7.6 (b). The transitions are observed to occur at the same value of the internal feedback fraction for both PCF and COF. Similar behaviour was observed for the narrow-waveguide diode laser in chapter 6, indicating that the same mechanisms are responsible for transitions into instability caused by phase conjugate and conventional optical feedback in both broad-area and narrow-waveguide devices.
7.5. Summary

Many authors have reported that operating a broad-area diode laser with phase conjugate feedback can force the laser to operate on a single-frequency. The current work has shown, however, that although single-mode operation can be attained at the scale of the diode laser longitudinal mode resolution, the external cavity modes of the system are not suppressed. The output also shows significant noise at the external cavity frequency, indicating dynamic instability.

These observations differ from the case of a narrow-waveguide diode laser with phase conjugate feedback. Such feedback has been shown to induce stable single-mode operation at both the external cavity and solitary diode longitudinal mode spacing frequencies. It is unclear whether such stable single-mode operation can be achieved with the broad-area diode laser with higher feedback fractions than have currently been demonstrated with the phase conjugate crystal.

The comparison of the transition into instability between the two systems (COF and PCF) shows that for low feedback levels the systems behave similarly for similar feedback levels. The largest differences between the two systems occur at higher feedback levels.
8.1. Introduction

Due to the strong coupling of the refractive index to the carrier density in a semiconductor diode laser, a direct modulation of the injection current results in a modulation of both the output power and the output frequency. The resulting output optical frequency spectrum consists of a series of sidebands developed around the centre lasing frequency. The output power varies sinusoidally at the modulation frequency. A diode laser operating in such a state with a very broad bandwidth (large number of sidebands) would readily find application in a number of areas. These include accurate frequency measurement, optical frequency division multiplexing, short pulse generation, laser cooling of atoms, and optical metrology [63,236].

The introduction of optical feedback into the diode laser significantly alters the modulation characteristics. As shown in figure 8.1 the frequency deviation (proportional to the modulation index) is resonantly enhanced for modulation frequencies around the external cavity mode frequency [173,223,224]. This enhancement is predicted to decrease with a decrease in the feedback fraction or the external cavity length. For a long external cavity (~300 mm), at any particular detuning of the modulation frequency from the longitudinal mode spacing of the external cavity, there is a maximum useable modulation power above which there is a transition to a dynamically unstable state, similar to that found in regime IV (coherence collapse). This has been observed in both directly [230-232] and indirectly [168,169] modulated external cavity diode lasers. This maximum modulation power, which is dependent upon the modulation frequency detuning and the effective reflectivity of the external reflector, implies that the system has a maximum modulation bandwidth. This form of coherence collapse significantly limits the attainable FM bandwidth from an FM diode laser, compared to the several THz bandwidths potentially available with this and other broad gain bandwidth FM lasers [176].

Larger bandwidths are potentially attainable by decreasing the external cavity length, as the modulation frequency must be increased to match the external cavity frequency. This
leads to the possibility of operating diode lasers with very short or integrated external cavities at high modulation frequencies. As the external cavity length is reduced, however, the system is further complicated because distinction arises between the external cavity resonant frequency ($f_{ec}$) and the external cavity diode laser resonant frequency ($f_{ecd}$). This occurs due to differences in the relative photon lifetimes for the two cavities and leads to theoretical predictions of induced dynamic (non-FM) states in short external cavities [235,300]. The coherence collapsed state induced for longer external cavities is not predicted to occur in the short cavity limit [236,301].

The current study examines the effect of cavity length on the modulation characteristics of directly modulated diode lasers with feedback. In particular, the effects of strong optical feedback on the modulation bandwidth as a function of cavity length, and the transition into instability versus cavity length are considered. It is found that as expected the modulation bandwidth is enhanced by the presence of feedback for long external cavities, but as the external cavity length is shortened the feedback has the effect of suppressing the modulation bandwidth. Mode locked operation is not observed in the current work.

The current study also examines the effect of optical injection on a frequency modulated external cavity diode laser; ie a frequency modulated diode laser with optical injection and
optical feedback. Modulation, injection, and feedback are each known to cause dynamic instabilities independently. Thus, over the full parameter range it would be expected that the dominant output state would be unstable. Therefore, only strong injection (phase locked master and slave) and strong feedback (regime V single-mode output) are considered. In particular the effect of the injection locked state on the output modulation bandwidth is investigated. It is found that larger bandwidths are possible in the injection locked FM ECDL, than in the free running FM ECDL, by virtue of the suppression of the modulation induced coherence collapse in the injection locked FM ECDL. However, much higher modulation powers are required to obtain comparable FM indexes.

![Graph showing suppression of frequency modulation index in FM signal generation when a cw single-mode signal is injected into a direct frequency modulated diode laser](image)

*Figure 8.2. Suppression of frequency modulation index in FM signal generation when a cw single-mode signal is injected into a direct frequency modulated diode laser. After [85].*

Previous studies have reported on the effects of optical injection on the modulation characteristics of a directly modulated diode laser [104, 302-307]. If the injected master signal has the necessary power and detuning to phase lock the two lasers, then the modulation index of the slave diode laser is significantly suppressed at any given modulation power. This is shown in figure 8.2. This suppression is due to a reduction in the FM noise occurring in the injection locked state [104]. No studies have previously reported the effects of optical injection on a frequency modulated external cavity diode laser.
8.2. Experiment

Figure 8.3. Experimental set-up for direct frequency modulation of diode laser with (a) optical feedback (section 8.3), and (b) optical feedback and optical injection (section 8.4).

The experimental set-up is shown in figure 8.3. The combination of optical injection (used in section 8.4) from a tunable diode laser, and optical feedback (from a plane mirror) is achieved as was described in section 5.2. Frequency modulation is achieved by applying a radio frequency signal to the dc bias of the diode injection current (with a Rhode Schwarz #SMP22 signal generator and bias Tee). The 850 nm STC diode laser (#LT50-03U) is used. The system diagnostics are the same as in section 3.2.1, with the addition of a fast (3 GHz) photodiode and a 2 GHz oscilloscope to monitor the output power versus time. The modulation index, $\beta$, is calibrated from the ratio of the amplitude of the carrier frequency to the first sideband pair (equation 2.41). When asymmetry in the sideband amplitudes occurs (indicating the presence of significant amplitude modulation), the average value is taken.
8.3. Frequency modulation characteristics of an ECDL

To examine the effects of variable external cavity length on the modulation characteristics of an external cavity diode laser, a long (~290 mm) cavity and a short (~51 mm) cavity system are examined and compared. In figure 8.4 the modulation index is plotted as a function of modulation frequency for a diode laser with feedback from a ~290 mm external cavity. In this plot the modulation power is fixed at 8 dBm. The modulation index at a fixed modulation power (or modulation voltage) is proportional to the modulation response, a linear function that is defined as the gradient of the maximum frequency deviation to the modulation current \((\Delta F/\Delta I)\), because the modulation index is proportional to the frequency deviation (equation 2.40) and the modulation current is proportional to the modulation voltage. The dotted line in the figure represents the modulation index of the solitary diode laser (i.e., with the external mirror removed). This has a constant value over the modulation frequency interval observed.

![Figure 8.4](image)

**Figure 8.4.** Modulation index as a function of the modulation frequency for an external cavity of length ~290 mm. The dotted line shows the flat modulation index for the solitary diode laser with no feedback. The arrow indicates the magnitude of the difference between the external cavity resonant frequency and the external cavity diode laser resonant frequency.

External feedback fraction is 0.7, injection current is 55 mA.

The modulation index of the external cavity diode laser is resonantly enhanced, compared to the modulation index of the solitary diode laser, at a modulation frequency of ~516.2 MHz. This modulation index enhancement is due to near mode resonances between
the external cavity longitudinal mode frequencies and the driving modulation (ie the external cavity modes enhance the modulation sidebands). The centre resonant frequency is found to depend on the amount of feedback power. As the feedback is decreased the peak shifts to shorter wavelengths and is reduced (as predicted by theory [173] and previously observed [223]). The magnitude of the difference between the two external cavity resonance frequencies for this external cavity length is shown in the figure. This frequency difference (1.8 MHz) is significant compared to the peak width (0.9 MHz). The relative values of the diode laser front facet reflectivity and the external feedback field determines the dominant operating frequency of the ECDL. For a resolvable difference in the cavity resonant frequencies two peaks should be observed if the resonance of both cavities is equal. Only one peak is observed for all values of the external feedback fraction. This indicates that one of the external cavity resonant frequencies is significantly dominant over the other in this system.

Figure 8.5. Output power versus time (columns 1 and 4) and optical frequency spectrum (columns 2 and 3) for a directly modulated external cavity diode laser with $R_{ext} = 0.70$ and $l = 290$ mm (columns 1 and 2) and for a directly modulation diode laser with no feedback (columns 3 and 4). The modulation power for each row is indicated at the left of the figure. The vertical power scale is the same in each plot (20 dBm represents ~90% modulation of the dc level). For each plot $f_m = 516.2$ MHz and $I = 55$ mA.
In figure 8.5, the output power versus time and the output optical frequency spectrum for the frequency modulated diode laser with optical feedback is compared to the frequency modulated solitary diode laser (with no feedback). The first two columns show the FM external cavity diode laser output with increasing modulation power. The modulation frequency corresponds to the peak in the modulation index versus modulation frequency (ie figure 8.4). As expected from figure 8.4, the modulation index of the solitary diode laser (column 3) is much lower than that of the ECDL for any value of the modulation power.

As the modulation power is increased the modulation index (of the ECDL) increases until at a certain modulation power there is a transition into an unstable multi-mode state. This state is characterised by multiple peaks at the external cavity mode spacing (and modulation frequency). Similar frequency spectra were observed in the diode laser with asymmetric feedback in chapter 3 (figure 3.14) and the regime IV diode laser with optical feedback in chapter 6 (figure 6.8). Such transitions have previously been observed in both directly and indirectly modulated diode lasers with feedback, and the induced multi-mode state has been considered to be indicative of the dynamically unstable coherence collapse regime [168]. However, the dominant temporal feature for this state is the strong amplitude (power) modulation, as opposed to a chaotic output power for regime IV. The solitary diode laser also shows a transition into a distinct state at high modulation powers. However, in this state the spectrum is broadband with no distinguishable mode features.

At low modulation powers the modulation of the output power is below the sensitivity of the photodetector and oscilloscope. At higher modulation powers the output power is sinusoidally modulated at increasing levels. The fluctuation compared to the dc output power is ~90% for a modulation index of 20 dBm at the injection current used. This was calibrated from the magnitude of gain switched pulses observed for large signal modulation.

The introduction of feedback has the effect of reducing the power modulation (by ~ 5 %) for a given modulation level of the injection current. This occurs regardless of the modulation frequency (with respect to the external cavity frequency). It is also observed at any injection current. Thus, it is not just a consequence of the change in the dc level of the output power due to carrier injection. As described in chapter 3, the output power increases with feedback for low injection currents and decreases with feedback for high injection currents. The reason for the reduced amplitude modulation is unclear. However, it indicates that the current modulation index to the diode laser is not significantly altered by the presence of feedback. The role of the linewidth enhancement factor may be important for this.
Due to the enhancement of the frequency modulation index in the ECDL, and the slight reduction in the amplitude modulation with feedback, the ratio of the amplitude modulation index to the frequency modulation index is much lower than for the solitary diode laser. This results in a lower FM sideband amplitude asymmetry in the ECDL compared to the solitary diode laser.

Figure 8.6. Modulation index as a function of the modulation frequency for an external cavity of length ~51 mm. The dotted line shows the flat modulation index for the solitary diode laser with no feedback. The arrow indicates the magnitude of the difference between the external cavity resonant frequency and the external cavity diode laser resonant frequency. External feedback fraction is 0.7, injection current is 55 mA.

As the external cavity is reduced the modulation characteristics are altered. The modulation index versus modulation frequency is shown in figure 8.6 for an external cavity of length ~51 mm. Similar to the longer cavity case a single peak of modulation index is observed for a single cavity resonance, although for the shorter cavity the difference in the two external cavity resonant frequencies is much larger (95 MHz). There are two main differences between the short and long cavity case. Firstly the peak is much broader, and secondly the maximum modulation index of the external cavity diode laser is much lower than that of the solitary diode laser. Thus, the feedback has the effect of suppressing the modulation index (as opposed to enhancement for longer cavities). Such suppression has not previously been observed to the author’s knowledge.

The optical frequency spectrum for increasing modulation power is shown in figure 8.7 for the short external cavity diode laser compared to the solitary diode laser. The modulation frequency corresponds to the peak in the modulation index in figure 8.6. At any given value
of the modulation power the modulation index with feedback is lower than the modulation index with no feedback, as expected from figure 8.6. The same transitions into multi-mode output, as observed for the longer cavity, are also observed for the short cavity case. The dominant temporal feature is again the strong modulation of the output power. Although this is not shown, similar characteristics of the output power versus time to the long cavity case (figure 8.5) are observed, i.e. there is a slight decrease in the output power modulation due to the presence of the feedback. This indicates that there is no significant change in effective current modulation caused by the feedback that may explain the suppression of the modulation index.

**Figure 8.7.** Optical frequency spectrum for a directly modulated external cavity diode laser with an external feedback fraction \( R_{\text{ext}} = 0.70 \) and a \( \sim 51 \text{ mm} \) external cavity (left column), and for a direct frequency modulated solitary diode laser (right column). The modulation frequency is 2.94 GHz and the diode laser injection current is 55 mA. The modulation power (in dBm) for each spectrum is indicated at the left of the figure.

Although mode-locked output has been predicted to occur [176], and obtained in ref [225-229] for similar experimental conditions, no mode-locked state has been observed in the current experiment. However, the sensitivity of the detection system limits observable output power variations to \( > 20\% \) of the dc output power level. Lower amplitude mode-locked pulses
may thus be occurring. Additionally, no distinction is observed between the induced instabilities for long and short cavities. Although the output power varies similarly (on the time scale of the modulation frequency) and the optical frequency spectra show similar characteristics, they may still represent distinct dynamic states (on a faster time scale).

![Figure 8.8. Normalised frequency deviation versus modulation frequency. Each data point represents the maximum resonant frequency deviation (maximum modulation index) for the modulated diode laser with feedback. Diode laser injection current is 55 mA. External feedback fraction is 0.70.](image)

In figure 8.8, the normalised frequency deviation is plotted as a function of modulation frequency. The normalised frequency deviation is defined as the ratio of the maximum frequency deviation (maximum modulation index) of the external cavity diode laser divided by the frequency deviation of the solitary diode laser. Each data point thus represents a different external cavity length. The frequency deviation is proportional to the modulation response as the modulation current is kept constant. For modulation frequencies below 1 GHz the bandwidth is significantly enhanced by the optical feedback. Above ~2.5 GHz, the effect of the optical feedback is to suppress the modulation bandwidth at all modulation frequencies.

The reduction in the enhancement of the modulation index as the external cavity length is reduced is predicted theoretically (figure 8.1) [173]. However, suppression of the modulation index for short external cavities (< 60 mm) (high modulation frequencies) is not predicted. It is unclear whether further decrease in external cavity length (hence increase in modulation frequency) will lead to a continuation of the trends (ie suppression of the modulation index relative to the diode laser with no feedback) or may lead to an enhancement
because the two resonant frequencies are significantly distant. A different experimental configuration is required to further increase the modulation frequency as losses increase rapidly with modulation frequency above 4 GHz in the current experimental set-up. It is important to examine how the system behaves in the limit of very short external cavities for the application of integrated FM diode laser devices.

![Figure 8.9](image-url)

**Figure 8.9.** Maximum frequency deviation as a function of the modulation voltage (proportional to modulation current) for a range of external cavity resonant frequencies (as indicated in the figure). The highest modulation voltage for each cavity length (joined by the dotted line) represents the transition from FM into a multi-mode optical frequency spectrum. Injection current is 55 mA. $R_{\text{ext}} = 0.85$.

The maximum modulation index attainable before the transition from FM lasing operation to multi-mode operation is found to vary dependent on the modulation frequency. The maximum frequency deviation (defined in equation 2.40) is plotted as a function of modulation current for a range of different external cavity lengths in figure 8.9. In each case the modulation is applied at the frequency of maximum modulation index enhancement for each cavity length (peaks as shown in figure 8.8). It is observed that the modulation induced multi-mode state occurs at much higher modulation currents for shorter external cavities, but that this corresponds to a much lower frequency deviation due to the suppression of the modulation index for such cavity lengths. This indicates that shorter external cavities are less susceptible to FM induced dynamic instabilities (as the modulation power can be driven much higher), which agrees with the observations of chapter 4.
8.4. Optical injection of an FM ECDL

The suppression of the modulation index (hence fm noise) of a solitary diode laser by optical injection [104,302-306], and the suppression of feedback induced instability by optical injection (investigated in chapter 5) indicates possible advantages of optical injection for the frequency modulated operation of external cavity diode lasers. The experimental set-up is shown in figure 8.3 (b). The technique for combining feedback and injection is as used in chapter 5. The effects of optical injection on the frequency modulation characteristics of an external cavity diode laser are shown in figure 8.10. The output modulation index, $\beta$, is plotted as a function of the modulation voltage (proportional to the modulation current), for the free-running FM ECDL, the injection locked FM ECDL and the frequency modulated solitary diode laser with no feedback.

![Graph showing modulation index vs. modulation voltage for different cases](image)

*Figure 8.10. Modulation index ($\beta$) as a function of the modulation power. (a, b): free running FM ECDL; (c ,d): injection locked FM ECDL; and (e): frequency modulated solitary diode laser. Modulation frequency in (a), (c), and (e) is 473 MHz, and in (b) and (d) is 467 MHz. External cavity length is ~317 mm. Injection current is 55 mA.*

For the free running FM ECDL (close to zero detuning) the modulation index increases with modulation power until at a certain point coherence collapse is reached (curve a). If the detuning is increased (curve b) then at any given modulation power the modulation index is
reduced, but the modulation current can be driven higher before transition to coherence collapse, thus a slightly larger bandwidth is found.

For the injection locked FM ECDL (strong signal injection) the analogous curves (c and d) show that the injected signal significantly reduces the modulation index at any modulation current but suppresses the transition to coherence collapse. Thus, larger FM bandwidths are achievable because the FM transition to coherence collapse is suppressed and higher modulation powers may be utilised. If the injected signal power is less than that necessary to lock the two lasers, then a dynamically unstable state is reached, similar to that observed in the previous chapter. If the injected signal beam power is very much less than the power of the slave laser then there is no observable effect on the frequency spectrum.

The modulation index of the solitary diode laser is also shown in the figure. The modulation response (proportional to the slope of the graph) is much lower for the diode with no feedback, however, the transition into instability limits the modulation bandwidth. The injected signal thus competes with the optical feedback enhancement of the modulation and suppresses the modulation index of the ECDL, bringing it back towards that of the solitary diode laser.

No transition to coherence collapse in the injection locked ECDL has been observed up to the maximum modulation power available with the current experimental apparatus (5 Volts peak-to-peak), which is close to the damage threshold of the diode. This corresponds to an increase in maximum modulation index by a factor of approximately two. However, it is expected that larger increases in obtainable FM bandwidths should be achieved with modified experimental arrangements. In the present experimental set-up there is a limit to the amount of feedback provided from the external mirror (higher feedback would lead to greater feedback induced bandwidth enhancement at this cavity length) due to the intra-cavity beam splitter, and the requirement of strong signal injection. Injecting into the back facet of the laser diode would allow larger feedback fractions.

The reduction in the modulation index with injection locking has previously been reported for solitary frequency modulated diode lasers subject to injected signals [85,103,104]. It was reported that this reduction is proportional to the injection power ratio, ie at high injected signal powers the output modulation is significantly suppressed, but it is not effected at low injection power ratios. Similar results have been observed in the current work. However, the suppression of the modulation index was found to be significantly larger with an ECDL as opposed to a laser diode. This may be considered equivalent to a suppression of the FM noise, and hence leads to linewidth reduction [98-100], which is expected to be much
greater for an injection locked ECDL compared to an injection locked laser diode by virtue of the optical feedback.

![Optical frequency spectra of (a) free-running frequency modulated ECDL, and (b) injection locked ECDL. Modulation frequency is 470 MHz. Injection current is 55 mA.](image)

Figure 8.11. Optical frequency spectra of (a) free-running frequency modulated ECDL, and (b) injection locked ECDL. Modulation frequency is 470 MHz. Injection current is 55 mA.

The disadvantage of providing larger bandwidths due to injection locking an FM ECDL is that the corresponding amplitude modulation is larger. This is shown in figure 8.11 where (a) is the free running FM ECDL at a modulation index of 1.5, and (b) is the injection locked FM ECDL at a similar modulation index. The injection locked signal shows substantial asymmetry. This indicates that the injected signal has a larger effect on the carrier density inside the diode laser active layer than the optical feedback field.

The injection locking experiments have also been performed with an FM ECDL whose modulation is provided indirectly via an intra-cavity phase modulator. The modulator is a Brewster cut lithium niobate crystal coupled to an inductor chosen to make the combined circuit resonant close to the cavity longitudinal mode spacing, which is driven by an amplified signal from the signal generator. The bandwidths obtainable with the intra-cavity FM ECDL (with no injected signal) are significantly greater than for the directly modulated FM ECDL, because of the increased modulation enhancement due to multiple passes in the system. The accompanying amplitude modulation is much lower for indirect modulation because there is less carrier heating within the diode laser. When such a system is injection locked the suppression of the modulation index is much greater than for the directly modulated ECDL (by a factor of 100). While this modulation index suppression is assumed to be accompanied by a suppression of the transition to coherence collapse, because the index suppression is so
large the modulator must be driven with much higher powers. This has not been done due to the possible risk of damage to the modulation crystal. Thus, the bandwidths obtained in the injected-locked phase-modulated FM ECDL are much less than those obtained with the unlocked phase-modulated FM ECDL.

8.5. Integrated devices

The motivation for studying frequency modulated diode lasers with optical injection is to generate wide bandwidth semiconductor laser sources. The results indicate the possibility that these devices could be integrated on a single chip that benefits from the extra stability of a self-locked diode laser coupled with separate frequency modulation via self-locked intracavity phase modulation.

Figure 8.12. Integrated device designs for FM laser diodes which are not susceptible to modulation induced coherence collapse. AL: active laser section, PIN: modulator section, PW: passive waveguide section, CAM: amplitude modulation compensation Facets f1 have a high reflectance coating and facets f2 have a low reflectance coating.

As for the injection locked laser diode with optical feedback (chapter 5), integrated device designs are proposed to exploit self-locking and intracavity phase modulation. Figure 8.12 (a) is similar to the OFILD shown in figure 5.8 (c) except it has a separate modulator section which has the same layer structure as the laser section but which is reverse biased and modulated to achieve FM ECDL operation. The device shown in figure 8.12 (b) additionally
incorporates an active waveguide section which is biased to independently compensate for amplitude modulation as has been demonstrated in mode-locked diode lasers [228]. Such devices have the potential to be the very broad bandwidth, compact, FM lasers suitable for application in frequency division multiplexing and optical metrology. Developments in suitable impurity induced disordered and quantum well intermixed semiconductor materials to fabricate these passive/active multi-section devices are emerging at this time [308,309]. Further investigation of the stability regions of frequency modulated external cavity diode lasers with very short cavities (hence much higher modulation frequencies) are necessary to determine whether enhancement or suppression of modulation bandwidth occurs at such cavity lengths, and whether windows of FM lasing operation exist.

8.6. Summary

The aims of the investigations presented in this chapter into the modulation characteristics of diode lasers with optical feedback with variable length external cavities are to examine the feasibility of integrated FM devices. The observed effects of external cavity length on the enhancement of the modulation bandwidth from a frequency modulated diode laser initially indicate that for enhanced modulation index, only long external cavity feedback is useful (as suppression is observed for shorter cavity lengths). However, the short cavity system is less susceptible to modulation induced instabilities. It is important to examine the effects for much shorter external cavities and higher modulation frequencies, and to further explore the dynamic states observed with short cavities to explain correlation with previous studies. The role of the amplitude modulation, and its suppression with optical feedback also needs to be further explored.

The studies on the injection locking of frequency modulated external cavity diode lasers has shown that similar behaviours are observed to injection locked solitary diode lasers. That is, the modulation bandwidth is suppressed by the injection. However, the modulation induced dynamic instability caused by the optical feedback is also suppressed. These results may be incorporated in short cavity integrated devices, similar to the proposals of chapter 5.

Although primarily direct modulation has been considered, the extension of the results presented in this chapter to indirectly modulated diode laser systems is important, and needs further investigation, as the integrated devices rely on phase modulating elements.
9.1. Summary of results

- For a diode laser with on-axis symmetric feedback, the output power is reduced relative to the solitary diode laser output power (with no feedback) at high injection currents. This result has been explained as resulting from the reduction in both slope efficiency and threshold injection current due to the presence of feedback, when a spatially dependent coupling efficiency is taken into account. A model has been presented that predicts the output power as a function of injection current and external mirror tilt (for any orientation). Good qualitative agreement with the experimental observations has been demonstrated.

- The reduction in power for on-axis feedback, is accompanied, in certain types of diode laser, with multi-mode operation resulting from increased spectral and spatial holeburning at injection current above \( 1.2 I_{th}^{dl} \). This behaviour is absent in one type of diode laser (the 850 nm STC device) and present in several others.

- The effects of the external cavity length on the feedback characteristics vary dependent on the particular diode laser used. For the 850 nm STC diode laser coherence collapse is suppressed for external cavity lengths less than \(~80 \text{ mm}\). This is much longer than theoretically predicted or observed in other laser types.

- As the feedback phase is varied the output of the Nortel 1300 nm diode laser cycles through a series of stable states (at different wavelengths) and unstable states. The number of stable states and the relative phase values depends on the external cavity length and injection current. Preliminary theoretical predictions show some qualitative agreement with the observed patterns of behaviour.

- Variations in feedback phase (for the STC 850 nm diode laser) result in a sinusoidal variation in output power at low (regime III) feedback levels, and a triangular variation in output power at high feedback (regime V) levels. A theoretical model based on a standard rate equation analysis shows good agreement with the experimental observations.
Chapter Nine: Conclusion

- The injection of a single-frequency source into the active layer of a diode laser that is operating with feedback appropriate to generate dynamic instabilities (coherence collapse) can force the slave laser to operate on the single-frequency of the injected laser. This injection locking behaviour occurs regardless of the dynamic state of the slave laser.

- A diode laser with phase conjugate feedback shows characteristics, in terms of the output dynamics, which are different from those observed in a diode laser with conventional optical feedback. The main difference is observed at the transition between regimes IV and V. For PCF, this transition is characterised by a significant development of the intensity noise at external cavity mode frequencies, indicating some progression through high order dynamic states not observed in the COF case and possibly low frequency fluctuations. Several other distinct states are observed for PCF that have not previously been reported.

- The transition into regime IV from regime III occurs at similar values of the internal feedback fraction (ie taking the differences in coupling efficiencies into account) for COF and PCF. The transition from regime IV into the strong feedback regime V, however, occurs at significantly higher internal feedback fractions for the PCF case.

- A broad-area diode laser with phase conjugate feedback can be forced to operate on a single longitudinal mode of the laser. However, the modes of the external cavity are not suppressed at the phase conjugate reflectivities achieved to date. The progression of the optical and noise spectra into multi-mode (chaotic) behaviour for both cases is similar to that observed in the narrow-waveguide diode laser. There is no transition into an equivalent regime V (stable single-mode output) for the broad-area diode laser studied with feedback from a plane mirror.

- The effect of optical feedback in a directly frequency modulated diode laser is to enhance the modulation index for external cavities longer than ~100 mm, and to suppress the modulation index for shorter cavity lengths.

- Optical injection is found to suppress the modulation index of a frequency modulated external cavity diode laser. This suppression of the modulation index also suppresses the onset of coherence collapse (induced by the modulation) so that higher modulation indexes are possible. However, the required modulation power is significantly larger.

- The coupling efficiencies between the external fields and the diode laser active layer have been estimated for several arrangements by various methods and for various diode lasers. The highest coupling efficiencies (~0.7) are found for phase conjugate feedback into a narrow-waveguide diode laser (STC). Experimental measurements of these values have
not been reported previously. This is compared to coupling efficiencies of ~0.30 for the
same diode laser with conventional optical feedback and ~0.12 for an optically injected
field from a single-frequency tunable diode laser. The coupling efficiencies for a broad-
area diode laser (also not previously reported) have been estimated to be 0.10, and 0.50
for conventional optical and phase conjugate feedback respectively.

9.2. Implications of results

The studies on the effects of misaligned feedback are significant because they firstly
describe quantitatively the mechanisms that lead to the output power variations with external
mirror alignment that have been observed in many applied feedback systems. The spectral
hole burning observed in some types of diode laser is obviously a negative characteristic.
These results have significant implications for the practical methods utilised when optimising
the alignment of feedback systems and the output power that can be achieved with little
susceptibility to the onset of dynamic instability with technical noise perturbations. This
shows the need to examine the behaviour of different types of diode laser in a given system,
as some will be more appropriate for specific applications.

The observations of the effects of external cavity length, injection current, and feedback
phase on the stability regimes for two different diode lasers are significant because they
indicate the complexity of these systems. The many controllable variables (external cavity
length, injection current, feedback fraction), and the diode laser internal parameters (facet
coatings, internal loss, quantum efficiency, length, relaxation oscillation) all contribute to the
behaviour of the system. Characterisation of the controllable variables has been done for two
different types of laser diode. Both show different feedback characteristics. Isolating the
effects or relative importance of any one particular internal laser parameter is difficult to
achieve experimentally. The observations indicate areas for which the theory needs further
development. They also indicate the necessity for different types of diode laser to be tested for
a given application, as the feedback characteristics may be superior in some devices.

The studies on optically injecting diode lasers with feedback indicate that it may be
possible to generate a diode laser device that is insensitive or less sensitive to unwanted
feedback. Such a device would have significant applications in many areas, such as
communication systems, and optical data storage and retrieval, as it obviates the necessity for
expensive optical isolators and antireflection coatings on external surfaces.
The observations of the dynamic states induced by phase conjugate feedback and their comparison to conventional optical feedback are important because they add new insight into this field. The observation of distinct dynamic evolution with feedback for PCF as opposed to COF agrees with many theoretical predictions. Several distinct output states have been observed that have not previously been reported.

The behaviour of broad-area diode lasers with feedback adds to the understanding of such devices. Similar characteristics to the narrow-waveguide device with feedback are observed, although several new states are found. Additionally it indicates the necessity for frequency selectivity (with COF) and injection (with PCF) in order to obtain narrow linewidth single-mode output, as either PCF or COF individually does not generate single-frequency operation.

The results presented on the subject of short external cavity frequency modulated diode lasers and optical injection in frequency modulated external cavity diode lasers has lead to the proposition of a number of types of integrated diode laser devices for stable wide bandwidth operation. Such devices would readily find application in a number of areas, including optical frequency standard measurements, atom optics, and frequency division multiplexing.

The examination and comparison of coupling efficiencies in diode lasers with various types of feedback indicates appropriate values that may be used in theoretical simulations. In addition, it quantifies the benefits that can be obtained using phase conjugate mirrors for feedback and diode laser coupling.

9.3. Further research

The results of this thesis indicate a number of topics for further research. Firstly, a number of experimental areas would benefit from a more detailed analysis than has been carried out in this thesis or have not been investigated and are obvious extensions of this work. Secondly, the experimental results presented here indicate areas in which theoretical models can be addressed. Thirdly, several direct applications have arisen from these studies. These areas are discussed below.
9.3. Further research

Extensions of the current work:

The feedback that has been used throughout this research has been derived from either a phase-conjugate mirror or a conventional optical mirror (with or without an intracavity lens). An important tool for providing feedback that is commonly used in many applications is a refractive index grating. A grating allows greater frequency control of the feedback beam, and in many cases enhanced stability. Although many characteristics that have been observed in the current work would be similar if a grating was used instead of a plane mirror (for instance the behaviour with mirror misalignment), many characteristics would be significantly altered (for instance the system dynamics). The main difference is that a grating provides spectrally filtered feedback, typically at much lower feedback powers. Comparisons between the coupling efficiencies of grating feedback to mirror feedback for the same diode laser would also be beneficial.

Similarly, no effort has been made to mode match the feedback or injected fields in this research. It would be a beneficial study to examine the effects of better mode matching these fields, using at least two intracavity lenses, on the coupling efficiencies and the feedback behaviours.

An important question that has arisen throughout this thesis regards the differences in the behaviour of different diode lasers. In particular, the 850 nm STC diode laser is observed to behave better in most aspects than other device types. Given that the STC devices are no longer commercially available, it is important to understand the reasons for their superior characteristics. Possible areas of investigation include the linewidth enhancement factor, the relaxation oscillation frequency and damping rate, and the internal quantum efficiency.

A more complete analysis of the dynamics of narrow-waveguide diode lasers with phase conjugate feedback would include a comparison of the results presented here with those obtained with a faster phase conjugate mirror. It was determined that a broad-area or narrow-waveguide diode laser as a semiconductor conjugator was inappropriate for such use. However, conjugation via four wave mixing in Kerr like medium or in an atomic vapour could be a possible alternative.

The subject of broad-area diode lasers with feedback needs a more complete study. There have been many publications demonstrating single-mode output from these devices. However, no study has been reported on the frequency modulation of broad-area diode lasers. Many systems that require a frequency modulated source would benefit from the increased output power that can be achieved with a broad-area diode. The poor spectral output (multi-longitudinal mode operation) of these devices limits their appropriateness for frequency
modulation. Methods such as optical injection, which would suppress the modulation index, may nevertheless allow improved modulation characteristics and should be investigated.

**Theoretical modelling:**

Many of the results of this thesis have been interpreted as consistent with current models. There are, however, many results for which the current theoretical understanding or capabilities of the current theoretical models are inadequate. For this reason several areas can be identified that require further theoretical development. These include strong feedback, stability criteria, and phase conjugate dynamics. In general there is a requirement that the models and the experiments both need to be modified so that they are examining the same aspects of the problem. In many instances both experiment and theory are developed separately, and thus the experiments do not cover the same parameter ranges as the theory and visa versa.

Currently many models are being developed that are capable of predicting strong feedback behaviour. As previously mentioned, it is important to completely understand the behaviour of such systems, as they are the most commonly used in applications. The many experimental observations of strong feedback systems presented in this thesis indicate possible areas for which the theories could be addressed.

In the area of diode lasers with short external cavities, an ongoing collaboration exists with the University of Bangor, Wales. The aim is to provide better agreement between the experimental observations presented here and the theoretical models. In particular, the observations of the variation in transition points versus external cavity length, injection current and feedback phase. More experimental analysis (of different types of diode laser) and further modification of the theory (to account for a range of internal laser parameters), is necessary. A full theoretical description of the stability criteria that agreed with the experimental observations would have strong implications for the engineering of many laser diode systems. It would allow the tolerances of a particular diode laser to spurious reflection to be determined without the current requirement for extensive experimental analysis in each particular application.

From a more pure physics perspective, many theoretical analyses of the nonlinear dynamics of narrow-waveguide diode lasers subject to phase conjugate feedback have been published. The experiments performed here have shown that in some aspects qualitative agreement is reached. However, a number of new states have been experimentally observed that are not predicted by current models; these primarily occur for strong feedback. There are
various issues related to the nature of the phase conjugate mirror used, such as its response
time and penetration depth, and whether or not the feedback is frequency shifted, for which
the current models could be modified in order to test their appropriateness to the particular
experimental arrangement presented here.

Applications:

Results of this thesis have led to the proposal of two possible integrated semiconductor
devices, which would readily find application in many areas: the OFILD and the integrated
frequency modulation device.

Further research is needed to ascertain if the OFILD concept would work in a
laboratory bench set-up; similar to that depicted in figure 5.8 (a). This requires asymmetric
coated diode lasers with access to both front and rear facets; these are not commonly available
devices, as the back facet output is typically very low. Devices based upon these principals
are currently in the process of fabrication, and thus further research will be possible when
they become available.

The second applicable proposal to arise from this research involves diode lasers with
integrated modulation sections separated by passive waveguide sections (as depicted in figure
8.17). Further research can be done on the characteristics of diode laser with very short
cavities and with high modulation frequencies, to examine the feasibility of such devices
before they can be fabricated. Fabrication technology is improving rapidly towards the point
at which such devices will be possible.
# Appendix A: Diode Laser Parameters

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<td>N.D.</td>
<td>0.7 ± 0.1</td>
<td>N.D.</td>
</tr>
</tbody>
</table>
Notes to table:

1. The Nortel device is a pre-packaged wafer and is not commercially available.
2. Centre wavelength and mode spacing are measured on an optical frequency spectrum
   analyser at a resolution of 0.1 nm and at a diode laser injection current of \( I = 2 I_{th}^{dl} \).
3. Diode laser length is calculated from the observed longitudinal mode spacing.
4. Threshold injection current is a typical value for each device type.
5. Output power is average value from front facet measured at \( I = 2 I_{th}^{dl} \).
6. Free-running side mode suppression is measured with a Fabry-Perot interferometer
   at an injection current of \( 2 I_{th}^{dl} \).
7. The uncertainty in the wavelength, mode spacing, length, threshold current, output power,
   and side mode suppression indicates variations between diode lasers of the same type.
8. Front facet reflectivity is measured from the reflected beam of an injected source, which is
   aligned such that no light is coupled into the diode laser cavity.
9. Back facet reflectivity is measured from the ratio of the front to rear output power (for
   Nortel 1300 nm diode laser and Sony broad-area diode laser) or manufacturers
   specification (for other diode lasers).
10. Internal quantum efficiency, internal loss, and coupling efficiency to the optical feedback
    field, injected signal, and phase conjugate signal, are calculated in text. N.D.
    represents parameters that have not been determined.
### Appendix B: List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{v,h}$</td>
<td>output beam profile coefficients</td>
</tr>
<tr>
<td>$c$</td>
<td>speed of light in vacuum</td>
</tr>
<tr>
<td>$E$</td>
<td>electric field vector</td>
</tr>
<tr>
<td>$E_0$</td>
<td>electric field amplitude</td>
</tr>
<tr>
<td>$f_0$</td>
<td>centre lasing frequency</td>
</tr>
<tr>
<td>$f_r$</td>
<td>relaxation oscillation frequency</td>
</tr>
<tr>
<td>$f_{inj}$</td>
<td>injected signal frequency</td>
</tr>
<tr>
<td>$f_c$</td>
<td>conjugate signal frequency</td>
</tr>
<tr>
<td>$f_d$</td>
<td>solitary diode laser longitudinal mode spacing</td>
</tr>
<tr>
<td>$f_m$</td>
<td>modulation frequency</td>
</tr>
<tr>
<td>$f_{ec}$</td>
<td>external cavity resonant frequency</td>
</tr>
<tr>
<td>$f_{ecd}$</td>
<td>external cavity diode laser resonant frequency</td>
</tr>
<tr>
<td>$F_{P,\phi,N}$</td>
<td>Langevin noise terms</td>
</tr>
<tr>
<td>$g_{op,th}$</td>
<td>optical gain at laser threshold</td>
</tr>
<tr>
<td>$G(N)$</td>
<td>laser diode (carrier density dependent) gain</td>
</tr>
<tr>
<td>$I$</td>
<td>injection current</td>
</tr>
<tr>
<td>$I_{th}$</td>
<td>solitary diode laser threshold injection current</td>
</tr>
<tr>
<td>$I_{th}^{dl}$</td>
<td>external cavity diode laser threshold injection current</td>
</tr>
<tr>
<td>$I_p$</td>
<td>induced photocurrent in diode laser operated as photodiode</td>
</tr>
<tr>
<td>$J$</td>
<td>injection current density</td>
</tr>
<tr>
<td>$J_n$</td>
<td>Bessel function amplitude</td>
</tr>
<tr>
<td>$k$</td>
<td>propagation constant</td>
</tr>
<tr>
<td>$l$</td>
<td>external cavity length</td>
</tr>
<tr>
<td>$L$</td>
<td>solitary diode laser length</td>
</tr>
<tr>
<td>$n$</td>
<td>real part of (semiconductor) refractive index</td>
</tr>
<tr>
<td>$n''$</td>
<td>imaginary part of (semiconductor) refractive index</td>
</tr>
<tr>
<td>$N$</td>
<td>carrier density</td>
</tr>
<tr>
<td>$P$</td>
<td>photon number</td>
</tr>
<tr>
<td>$P_{int}$</td>
<td>interband polarisation</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>( P_{\text{pol}} )</td>
<td>macroscopic polarisation</td>
</tr>
<tr>
<td>( P_{\text{inj}} )</td>
<td>injected signal power inside slave laser cavity</td>
</tr>
<tr>
<td>( P_{\text{ext}} )</td>
<td>external injected power (measured in front of collimating optic)</td>
</tr>
<tr>
<td>( P_{\text{inc}} )</td>
<td>incident optical power (on front facet of photodiode)</td>
</tr>
<tr>
<td>( P_{\text{out}} )</td>
<td>output locked power</td>
</tr>
<tr>
<td>( P_{\text{out}1,2} )</td>
<td>experimentally measured output powers</td>
</tr>
<tr>
<td>( r_1 )</td>
<td>diode laser back facet reflectivity coefficient</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>diode laser front facet reflectivity coefficient</td>
</tr>
<tr>
<td>( r_3 )</td>
<td>external reflectivity coefficient</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>diode laser back facet reflectivity</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>diode laser front facet reflectivity</td>
</tr>
<tr>
<td>( R_{\text{eff}} )</td>
<td>effective facet reflectivity</td>
</tr>
<tr>
<td>( R_{\text{2'}} )</td>
<td>maximum effective reflectivity</td>
</tr>
<tr>
<td>( R_{\text{bs}} )</td>
<td>reflectivity of beamsplitter facet(s)</td>
</tr>
<tr>
<td>( R_{\text{mirror}} )</td>
<td>external mirror reflectivity</td>
</tr>
<tr>
<td>( R_{\text{ext}} )</td>
<td>external feedback fraction</td>
</tr>
<tr>
<td>( R_{\text{sp}} )</td>
<td>spontaneous emission rate</td>
</tr>
<tr>
<td>( R(n_{\text{th}}) )</td>
<td>recombination rate at threshold</td>
</tr>
<tr>
<td>( S(f) )</td>
<td>laser lineshape</td>
</tr>
<tr>
<td>( t_m )</td>
<td>phase conjugate mirror penetration time</td>
</tr>
<tr>
<td>( w )</td>
<td>output beam profile coefficient</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>linewidth enhancement factor</td>
</tr>
<tr>
<td>( \alpha_{\text{int}} )</td>
<td>solitary laser diode internal loss factor</td>
</tr>
<tr>
<td>( \alpha_{\text{abs}} )</td>
<td>power absorption coefficient</td>
</tr>
<tr>
<td>( \beta )</td>
<td>modulation index</td>
</tr>
<tr>
<td>( \Delta f )</td>
<td>detuning (injection)</td>
</tr>
<tr>
<td>( \Delta f_{\text{IL}} )</td>
<td>injection locking bandwidth</td>
</tr>
<tr>
<td>( \Delta f_{\text{cav}} )</td>
<td>cavity resonant difference frequency</td>
</tr>
<tr>
<td>( \Delta F )</td>
<td>maximum frequency deviation</td>
</tr>
<tr>
<td>( \Delta I )</td>
<td>modulation current amplitude</td>
</tr>
<tr>
<td>( \varepsilon_0 )</td>
<td>vacuum permittivity</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>dielectric constant</td>
</tr>
<tr>
<td>( \phi )</td>
<td>electric field phase</td>
</tr>
</tbody>
</table>
Appendix B: List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_i$</td>
<td>phase of injected signal</td>
</tr>
<tr>
<td>$\phi_{pcf}$</td>
<td>phase of phase-conjugate feedback field</td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>optical feedback coupling efficiency</td>
</tr>
<tr>
<td>$\eta_{inj}$</td>
<td>optical injection coupling efficiency</td>
</tr>
<tr>
<td>$\eta_{pcf}$</td>
<td>phase conjugate feedback coupling efficiency</td>
</tr>
<tr>
<td>$\eta_{pd}$</td>
<td>photodetection quantum efficiency</td>
</tr>
<tr>
<td>$\eta_{ext}^{dl}$</td>
<td>solitary diode laser external quantum efficiency</td>
</tr>
<tr>
<td>$\eta_{ext}^{ec}$</td>
<td>external cavity diode laser external quantum efficiency</td>
</tr>
<tr>
<td>$\eta_{int}$</td>
<td>solitary diode laser internal quantum efficiency</td>
</tr>
<tr>
<td>$\theta$</td>
<td>external mirror tilt</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>surface charge</td>
</tr>
<tr>
<td>$\tau$</td>
<td>external cavity round trip time</td>
</tr>
<tr>
<td>$\tau_{in}$</td>
<td>solitary diode laser internal round trip time</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>carrier lifetime</td>
</tr>
<tr>
<td>$\tau_p$</td>
<td>photon lifetime</td>
</tr>
<tr>
<td>$\omega_r$</td>
<td>relaxation oscillation angular frequency</td>
</tr>
<tr>
<td>$\omega_{nj}$</td>
<td>injected angular optical frequency</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>centre lasing angular frequency</td>
</tr>
</tbody>
</table>
Following is a list of refereed journal articles (that have been published, accepted for publication, submitted for publication, or are in preparation) and conference papers (presented or submitted) that have arisen from the research presented in this thesis. (*) refers to papers both presented at conferences and published as journal articles.

**Journal Articles**


• R. J. Jones, P. S. Spencer, J. S. Lawrence, and D. M. Kane, “Output power from semiconductor lasers subject to optical feedback with sub-wavelength external phase variations”, in preparation, 2001.


Conference Papers


• P. S. Spencer, D. M. Kane, J. S. Lawrence and D. M. Kane, “Chaotic dynamics in FM external cavity lasers”, Semiconductor and Integrated Optoelectronics (SIOE ‘99), Cardiff, Wales, April 1999.

• J. S. Lawrence, D. M. Kane and P. S. Spencer, “Coherence collapse in short external cavity semiconductor diode lasers”, Australian Optical Society Conference (AOS ‘99), Sydney, Australia, July 1999.

• J. S. Lawrence and D. M. Kane, “Stability of semiconductor diode lasers with phase conjugate feedback”, Australian Optical Society Conference (AOS ‘99), Sydney, Australia, July 1999.

• J. S. Lawrence, D. M. Kane, and P. S. Spencer, “Suppression of coherence collapse in semiconductor diode lasers with short external cavities”, Advanced Semiconductor Lasers and Applications (ASLA ‘99), Santa Barbara, California, USA, July 1999. (*)

• J. S. Lawrence and D. M. Kane, “Coherence collapse in semiconductor lasers with phase conjugate feedback”, Advanced Semiconductor Lasers and Applications (ALSA ’99), Santa Barbara, California, USA, July 1999. (*)
Appendix C: Publications


- J. S. Lawrence, and D. M. Kane, ‘Characteristics of a broad area laser diode with time delayed phase conjugate feedback’, Semiconductor and Integrated Opto-Electronics Conference (SIOE 2000), Cardiff, Wales, April 2000.


References


187 References


References


References


References


