Chapter 2

Experimental Implementation of Amplitude Death in Coupled Diode Lasers

2.1 Introduction

In the previous Chapter, we have introduced the control techniques using optical feedback and optical injection in diode lasers, and reviewed the different collective behaviors of mutually coupled diode laser systems, in particular, phase locking and amplitude death of complex dynamics. In this Chapter we present an experimental observation unveiling the route to amplitude death in an external-cavity diode laser subjected to optical injection. As has been discussed, in order to improve the diode laser characteristics in terms of narrowing of linewidth [1] and wavelength tunability [2], optoelectronic feedback [3] or optical feedback [4] or injection [5] in an external-cavity [6] is generally used. A semiconductor laser subjected to external optical feedback exhibits a large variety of dynamic behaviours, such as periodic and quasi-periodic oscillations, chaos [7], coherence collapse [8], and low-frequency fluctuations [9] or regular pulsations that degrade the laser characteristics. The low-frequency fluctuation/pulsation (LFF/LFP) regime is typically observed when laser diodes are pumped near threshold and subjected to moderate optical re-injection from a distant reflector. This complex dynamical regime is characterized by a succession of sudden drop-outs and slow recoveries of the laser's mean intensity in between the drop-outs [10]. The recovery process of LFF/LFPs has been described as a sequence of transitions among compound cavity modes [11, 12]. A complete understanding of LFF regimes has been under debate since the very first observation. There is no analytical or experimental picture showing how the dynamics of the injected laser depends on the parameters on a global scale [13]. The only map showing the various dynamical properties of the system for relatively large range of parameter space comes from experimentalists [14]. But from the experimental point of view, a complete characterization of low-frequency dynamics is also quite difficult, because of very diverse time scales involved in the dynamics. The LFF poses a serious problem in applications where a
constant average output power from the laser is desired [15]. It is thus important to investigate minutely the nonlinear dynamical behaviour induced by external optical feedback in an external-cavity diode laser (ECDL), and explore methods of suppressing or controlling chaos and LFFs. The external optical feedback can induce additional noise, which is considered as feedback-induced deterministic. On the other hand, it has been shown that noise characteristics of a free-running laser can be improved by injection locking techniques [16]. We wish to consider whether the optical injection can be used to suppress the feedback-induced noise, and study the effect of optical injection on the feedback-induced noise performance and the phase locking [17] behaviour of the ECDL system. Here 'phase' refers to intensity oscillation cycles and it is not related to the optical phase of the electric field.

Few experimental and theoretical studies have been performed on the quenching of the amplitude of the LFF via a second optical feedback [18] or optical injection from another laser [19]. But the detailed information about the phase locking and route to ultimate amplitude death is lacking, which is the crucial point we wish to pay attention to in the present and subsequent Chapters in the context of a mutually-coupled laser system [20]. The coupling between the lasers could be in either unidirectional [21, 22] or bidirectional fashion [12] leading to different kinds of output [23]. The mutually-coupled diode laser system is very interesting because of its potential application in a wide range of fields, specially in communications [24]. Apart from this, the coupled diode laser system also provides a simple and powerful tool to unveil the collective behaviour within a wide range of control parameter space. Among the collective behaviour, amplitude death can occur when two identical or non-identical coupled chaotic systems drive each other to a fixed point and stop the oscillations [25]. The amplitude death of low-frequency dynamics may arise in different scenarios. First, if the coupling between two diode lasers is sufficiently strong so that it can create a saddle node pair of fixed points on the limit circle when the natural frequencies of the diode lasers are sufficiently separated [26], amplitude death can occur. Secondly, if there exists a time delay in coupling when the frequency mismatch between the coupled lasers is zero, a variation in the time delay eventually leads to amplitude death [27, 28] of the laser output. In the second case, the time delay initiates a Hopf bifurcation [29] in which the two lasers pull each other off their limit cycles and collapse to a steady state. The most accessible control
parameters, from an experimental implementation point of view, are probably the injection current, the coupling strength and the time delay. The number of adjustable external and internal parameters and their combinations is so high that new dynamical regimes are still being observed by careful adjustment of the laser parameters. An important focus of this Chapter is to experimentally investigate some intriguing aspects of the collective behaviour and route to ultimate amplitude death of the low-frequency dynamics, and analyze the results theoretically in the next two chapters.

In our system of a single-mode ECDL (slave) [11, 30, 31], we present a novel scheme of stabilization by phase locking and suppression of LFPs via bi-directional coupling with a multimode free-running (master) diode laser having similar characteristics [32]. Optical injection locking [33] usually arises in one of the two ways: either both the lasers emit in the same phase (in-phase solution), or the phase difference between the laser outputs is \( \pi \) (out-of-phase solution). The in-phase locking produces constructive interference in the output whereas out-of-phase locking produces destructive interference. In our set-up, the ECDL is subjected to both delayed optical feedback from a reflector (grating) and bidirectional coupling of the light from a driving laser into the external cavity. This system is interesting from several viewpoints, as it can combine desirable features of both external-cavity lasers and injection-locked lasers. For example, feedback and injection can both contribute to a narrowing of the laser linewidth [34], while strong injection inhibits coherence collapse. For optical communications using a chaotic carrier, it has been predicted numerically that optical injection may enhance the bandwidth in an external-cavity semiconductor laser operating on a high-dimensional chaotic state [35]. This allows the possibility of higher data transmission rates. This interest in optically injected external-cavity semiconductor lasers motivates the characterization of their simplest modes of operation. The dynamical behaviour has been investigated theoretically, tracing a route from stability to coherence collapse at increasing injection levels [36]. In this Chapter we concentrate on the regimes of continuous-wave emission of the injected laser (slave ECDL), phase-locked on the master laser. We have found a new route to complete amplitude death in this purely optically-coupled diode laser system and obtained results for the locking of different dynamical regimes with low to high coupling strengths.
The organization of the Chapter is as follows. The design and characterization of an external-cavity diode laser is presented in Sec. 2.2. This is followed by discussion of experimental results of coupled diode lasers in Sec. 2.3. The conclusions are presented in Sec. 2.4.

2.2 Design and Characterization of a Tunable External-Cavity Diode Laser

The low quality factor of diode lasers makes them extremely sensitive to optical feedback. The actual effect of the feedback depends on phase, magnitude, and polarization of the light fed back to the laser, and also on the feedback distance (i.e. delay time). For various levels of optical feedback, five regimes with clearly distinguished characteristics have been experimentally identified [37] and also theoretically simulated [38]. These regimes apply to single-longitudinal mode diode lasers, although very much the same kind of behavior exists for multimode lasers as well. For very weak feedback (regime I), the laser linewidth is narrowed or broadened, depending on the phase of the feedback. When the feedback is increased, considerable line broadening occurs as a result of splitting of the emission mode, and consequent mode hopping (regime II). Further increasing feedback leads to stabilization of one of the external cavity modes, and single-mode operation with narrow linewidth is obtained for all phases of the feedback. This regime (III) covers only a small range of feedback ratio. When exceeding a certain critical value of feedback, interaction between undamped relaxation oscillations and external cavity modes leads to chaotic behavior and linewidth broadening by several orders of magnitude [39, 40]. As the laser coherence length is tremendously decreased, this regime (IV) has been termed coherence collapse regime [41]. External-cavity diode lasers typically operate in the regime of strong optical feedback (V), where the laser linewidth is significantly narrowed and stable operation obtained. Optical feedback also affects the relative intensity noise of the laser. The RIN is low for weak to moderate feedback levels (regimes I to III) but increases drastically in the coherence collapse regime. In regime V significant reduction of the RIN is observed if only single-mode operation is maintained [42, 43].
\textbf{2.2-1 Elements for Tunable ECDL}

The external cavity-diode laser is basically composed of diode laser, dispersive element, base plate, piezoelectric disk, and good electrical control for temperature and current. We have used (Advanced Laser Systems LA-5C-830) semiconductor laser for external cavity. The aluminum base plate on which the diode laser holder and grating mount to be fixed in order to make the external cavity setup. To reduce movements due to vibration of the cavity we mount base plate on small soft rubber cushions and to avoid the thermal changes, the base plate is temperature controlled using heater. In addition to controlling the temperature of the base plate, we independently control the temperature of the laser diode. Finally, to avoid air currents interfering with temperature control we enclose the entire laser system in a small insulated box. The laser system also require a small amount of electronics. A stable low noise current source is needed to run the laser, and temperature control circuit is used to stabilize the diode and baseplate temperatures. In order to give the angular movement to the grating we put a piezoelectric disk behind the grating mount. The piezoelectric disk are solid state (ceramic) actuator, that convert electrical energy directly into mechanical energy by motion of extremely high resolution. In our external cavity setup, we use piezoelectric disk which is inserted between the grating mount adjustment screw and the movable face of the mount in order to rotate the grating about a vertical axis and alter the cavity length with electric control. Each PZT element consists of a thin smaller diameter silver plate piezoelectric slice is attached in the center with adhesive around its edge. When voltage is applied, the piezoelectric stress causes the backing to dish on the opposite side. Two such elements can be attached back to back, doubling the displacement of a single one, by lightly soldering the adjacent brass backings at four place around their circumference. After the PZT is assembled and wired, the grating is glued to the mount, the PZT should be inserted between the mounting plate and the ball end of adjusting screw as shown in Fig. 2.6.

\textbf{2.2-2 Pre-stabilization unit of ECDL}

The lasing wavelength of diode laser is proposnal to its band gap and the bandgap of diode varies with temperature and current. These variation affect the stability of the output wavelength, where temperature increases, the photodiode that is present to detect drop in
output and increase the drive current. High drive current increase the optical output and hence temperature. The current source ensure the drive current input to the laser diode never exceeds the allowable limit, and the temperature controller function to maintain the temperature of diode laser in the acceptable range. Precise control of the temperature of both the base plate and laser diode is essential for long term reliable operation of laser at a certain wavelength. We use the a film temperature sensor to measure the temperature of base plate and used a temperature controller to activate the heater. We put some vacuum grease between the sensor and the base plate to make sure that there is good thermal conduction. Frequency shift in diode laser caused by active layer temperature rise and carrier density changes. And the carrier density fluctuation effect on the frequency shift can be reduced by driving current control. The current stabilization make it possible to improve the frequency stability but requires simultaneous temperature stabilization, since at a constant current, the laser output power abruptly raises with decreases temperature Fig. 2.7. Precise control of temperature of both the base plate and diode laser itself is essential for the long term reliable operation of diode laser at a particular wavelength. A detailed discussion about temperature control has been given in [48]. The sensing element for the servo is a small thermistor, which is part of bridge circuit. The amplified and filtered error signal drives a heater. The temperature control circuit which drives the heater is shown in Fig. 2.1. Heating is much simpler since it only requires the attaching of film heater to the base plate. To keep the baseplate controlled it is necessary that it be at least 1-2°C above the room temperature, and the diode laser must be an equal amount hotter than the baseplate. The precise control of injection current of diode laser is also highly desirable to an external cavity diode laser system which can be achieved by high precision current controller. The laser diode output depends on the input current to the laser hence the use of current controller circuit is required. It is well known fact that as the current input to the laser diode increases the power output of the diode increases. This not only results in decrease in the linewidth of the power spectrum of the laser but it also result in blue shift of the spectrum as more and more higher energy states in the energy band of diode gets occupied. Therefore, controlling the current input to the laser diode is must. The circuit that we have used to make the current controller in our lab is similar to the [48] with only difference that we have used op07 instead op05
Figure 2.1: The circuit diagram of temperature controller [48]
operational amplifier. The circuit diagram is shown in Fig. 2.2. The output of the external cavity diode laser can be tuned by changing the current as shown in Fig. 2.10. The variation of lasing threshold with temperature is shown in Fig. 2.11. In an external cavity diode lasers, the effect of optical feedback can be analyzed by including feedback terms [44] in the rate equations solitary diode laser. Various technologies have been developed for reducing diode laser linewidth and for facilitating their wavelength tuning and also the variety of different ECDL designs is huge as they have been used and designed for several different applications. Most of the designs are based on one of the two basic configurations, the Littrow configuration (Fig. 2.3) or the Littman-Metcalf configuration (Fig. 2.4). The Littrow structure is simple and thus easier to stabilize, but it has a problem of varying output beam pointing associated with laser wavelength tuning which is made by rotating the grating. The Littman-Metcalf configuration removes this problem, although at the expense of increased complexity. But the grating used in littrow configuration have the advantage of maximum efficiency (or blaze) at specific wavelength because the groove spacing and blaze angle determine the distribution of energy. Despite the fact that ECDLs have been extensively developed and used in research laboratories and in commercial applications already for more than two decades, many new implementations have been reported also lately [45, 46, 47]. One of the simplest design of ECDL in perfect littrow configuration is developed in our lab and used in this thesis. The principle of the Littrow configuration External-Cavity Diode Laser is shown in Fig. 2.5. The 1st order reflection from the grating is used for optical feedback, while the laser output beam is obtained as the zeroth order beam from the reflection grating. The laser frequency can be tuned by rotating the grating and/or by tuning the laser cavity length. In order to achieve large mode-hop free tuning range, the grating angle and the laser cavity length must be synchronously varied so that the grating dispersion curve follows the lasing mode of the cavity. To calculate the Littrow angle we use the reflection grating equation:

\[ d(\sin \alpha + \sin \beta) = m\lambda. \]  

(2.1)

where \( \alpha \) is the angle of incidence, \( \beta \) is the diffraction angle, order of diffraction \( m \). For perfect Littrow configuration \( \alpha \) should be equal to \( \beta \). We use an 1200 lines/mm reflection grating, mounted on a block in our setup, we take \( \lambda = 830 \text{ nm} \), then Littrow angle \( \theta = 29.94^\circ \). The
Figure 2.2: The circuit diagram of diode laser current control [48]
Figure 2.3: The schematic of experimental set-up for ECDL in a Littrow configuration.

Figure 2.4: The schematic of experimental set-up for ECDL in the Littman-Metcalf configuration.
cavity length and the distance from the point of rotation of the grating arm to the point at which the laser beam intersects the grating were chosen so as to satisfy the continuous criterion. This requires that the cavity length $L$ and grating angle $\theta$ change together such that

$$\frac{\Delta \lambda}{\lambda} = \frac{\Delta L}{L} = \frac{\Delta \theta}{\tan \theta}$$

(which follow from the diffraction grating equation, $m\lambda = 2d\sin \theta$). The collimation can be fine tuned using the adjustment screws of the grating mount. We use an 1200 lines/mm reflection grating, mounted on a block set at $\theta = 29.94^\circ$ to the laser beam. The diode laser threshold current is monitored while the grating angle is adjusted in both planes, until a drop in threshold indicates the onset of feedback from the grating. At this point the laser cavity is mounted inside the box. All further adjustment can be made without access to the interior of the cavity. The laser wavelength is now monitored with a monochromator along with power meter. The laser is now tuned towards the desired wavelength on iterative process of minimizing the threshold current (maximizing the feedback) and adjusting the diode laser block temperature is used to optimize the laser output power. Temperature stabilization is necessary for diode laser in order to provide stable frequency characteristic. We have developed a system that is simple to tune, convenient to use, and provides temperature measurement accurate to within $\pm 0.01^\circ C$. 

Figure 2.5: The schematic of working of Littrow configuration.
The schematic of the experimental set up of ECDL is shown in Fig. 2.6 where a single-mode tunable ECDL (Advanced Laser Systems LA-5C-830 semiconductor laser, with a grating in the Littrow configuration) is operated at a wavelength of 825 nm at a threshold current 63.0 mA from a well-stabilized home-made current controller within an accuracy of $\pm 0.01$ mA. The temperature of the ECDL is set by a home-made temperature controller at 23.25°C within an accuracy of $\pm 0.01$°C. The diode laser is subjected to self-feedback from grating. The self-feedback strength is adjusted by a piezo-disk in order to get the perfect Littrow configuration. The length of the external cavity is set to 4.6 cm (round-trip time = 0.306 ns). A fast avalanche photodiode (Hamamatsu C5331-02) is used to monitor the ECDL intensity, which is simultaneously recorded with a digital oscilloscope (Tektronix TDS350, resolution = 2.5 ns). We have checked the tunability of our ECDL by applying the proper voltage to PZT as shown in Fig. 2.8. When we adjust the self-feedback at $4.5 \times 10^{-4}$ then the ECDL shows low frequency fluctuations as shown in Fig. 2.12. If we further increase the feedback strength $6.3 \times 10^{-4}$ then the external cavity diode laser start to onset of low frequency pulsations. Now at the coupling strength $7.2 \times 10^{-4}$ and injection current 63 mA, the ECDL shows the clear evidence of low frequency pulsations as shown in Fig. 2.13.
Figure 2.7: Experimentally observed external-cavity diode laser output power (in microwatts) versus temperature (in °C), showing that the power decreases as the temperature increases.

Figure 2.8: Experimentally observed external-cavity diode laser output power (in microwatts) versus wavelength (in nanometer), showing the tunability in wavelength as the PZT voltage changes. The curves are for voltage (a) 0V, (b) 15V, (c) 30V, (d) 45V, (e) 60V, (f) 75V, and (g) 80V
Figure 2.9: Experimentally observed external-cavity diode laser output power (in microwatts) versus injection current (in milliampere), showing threshold current changes as the temperature changes. The curves are for temperature (a) $T = 28^\circ$C, (b) $T = 29^\circ$C, (c) $T = 28.5^\circ$C, and (d) $T = 30^\circ$C.

Figure 2.10: Experimentally observed external-cavity diode laser output power (in microwatts) versus wavelength (in nanometer), showing the shift in operating wavelength. The curves are for injection current (a) $J_I = 62.5$, (b) $J_I = 63.5$, (c) $J_I = 64$, and (d) $J_I = 65.0$, at a fixed temperature $= 28^\circ$C.
Figure 2.11: Experimental plot of threshold current (mA) of external cavity diode laser versus temperature (°C), showing threshold current increases as the temperature increases.

The calculation of linewidth reduction of an external-cavity diode laser can be calculated with the cold-cavity linewidth $\Delta \nu_c$ of a solitary diode laser replaced by the cold-cavity linewidth $\Delta \nu_{ecd, c}$ of the complete external cavity:

$$\Delta \nu_{ecd} = \frac{c}{2\pi(n_d L_d + L_e)}\left(\alpha_m L_d - \ln\sqrt{R_1 R_3}\right).$$  \hspace{1cm} (2.3)

Consequently, the linewidth reduction in an ideal external-cavity diode laser can be given as

$$\frac{\Delta \nu_{ecd}}{\Delta \nu_0} = \left(\frac{\Delta \nu_{ecd, c}}{\Delta \nu_c}\right)^2.$$  \hspace{1cm} (2.4)

with $\Delta \nu_{ecd}$ denoting the linewidth of the external-cavity diode laser and $\Delta \nu_0$ being the linewidth of the solitary diode laser. In the coupled-cavity model, the influence of the laser diode output facet ($r_2$) is taken into account by the frequency dependent effective reflectivity $r_{eff}(\nu)$ of the external cavity [49]:

$$r_{eff}(\nu) = \frac{r_3 + r_2 e^{j2\pi \nu \tau_c}}{1 + r_2 r_3 e^{-j2\pi \nu \tau_c}}.$$  \hspace{1cm} (2.5)

Above $r_3$ has been taken as the reference plane, and the light reflected back by $r_2$ has been treated as a small perturbation with a leading relative phase, as represented by the positive sign of the external cavity round-trip time $\tau_e = \frac{2L_e}{c}$ in the numerator. In the case of strong optical feedback the actual lasing frequency $\nu$ is near the external cavity resonance.
\[ \nu_{ee} = \frac{l}{(\tau_d + \tau_e)}, \]

where \( l \) is an integer (longitudinal mode number) and \( \tau_d = \frac{2n_d L_d}{c} \) represents the round-trip time of the laser diode. The threshold condition for the laser oscillation is thus given by [50]:

\[ r_k e^{(g_{th} - \alpha_m) L_d} e^{2\pi \nu (\tau_d + \tau_e)} r_{eff}(\nu) = 1. \]  

(2.6)

The threshold gain \( g_{th} \) and oscillation frequency \( \nu \) can be obtained by writing the condition in Eq. (2.6) separately for the magnitude and argument. This provides two

\[ g_{th} = \alpha_m - \frac{1}{L_d} \ln(r_1|r_{eff}(\nu)|), \]  

(2.7)

\[ \nu - \nu_{ee} = -\frac{1}{2\pi(\tau_d + \tau_e)} \arg(r_{eff}(\nu)). \]  

(2.8)

Since the real and imaginary parts of the laser diode refractive index are coupled via the linewidth enhancement factor \( \alpha \), the resonance frequencies \( \nu_{ee} \) are not constants but depend on the threshold gain. The gain is modulated when the frequency is tuned and also the effective reflectivity \( r_{eff}(\nu) \) is also varied. The dependence of the real part of the refractive index on the threshold gain is approximately [50]

\[ n_d = n_{d0} + \frac{\alpha c}{4\pi \nu}(g_{th} - g_{th0}), \]  

(2.9)

\[ g_{th0} = \alpha_m - \ln \left( \frac{r_1 r_2}{L_d} \right). \]  

(2.10)

where \( n_{d0} \) is the refractive index and \( g_{th0} = \alpha_m - \ln \left( \frac{r_1 r_2}{L_d} \right) \) the threshold gain of the solitary diode laser. Combining this gain dependent refractive index with Eq. (2.7) and Eq. (2.8) gives

\[ \nu_{ee} = \frac{\alpha \ln(|r_{eff}(\nu)|) - \arg(r_{eff}(\nu))}{2\pi(\tau_d + \tau_e)}. \]  

(2.11)

where \( \tau_d \) is the round-trip time of the solitary diode laser without external feedback. Now, the actual linewidth \( \Delta \nu_{ecc} \) of the external-cavity diode is frequency dependent and can be calculated from Eq. (2.11) under very strong optical feedback the linewidth is given by [49].

### 2.3 Experimental setup for coupled diode lasers

The schematic of the experimental set up is shown in Fig. 2.16 where a second uncontrolled injection diode laser (Advanced Laser Systems LA-5C-830) operating at 830 nm with a solitary threshold of 73.0 mA is coupled to the ECDL via a polarizing beam-splitter. Special
Figure 2.12: Experimentally observed external cavity diode laser output power (in microwatts) versus time (in seconds), showing the low-frequency fluctuations at feedback strengths $\eta_f = 4.5 \times 10^{-4}$ for a fixed round trip time $= 0.306$ ns.

Figure 2.13: Experimentally observed external cavity diode laser output power (in microwatts) versus time (in seconds), showing onset of low-frequency fluctuations at feedback strengths $\eta_f = 6.3 \times 10^{-4}$ for a fixed round trip time $= 0.306$ ns.
attention has been paid to achieve a well defined coupling condition and time delay. The slave laser is subjected to self-feedback from its external cavity and a coupling from the master laser, and the master laser to only coupling from the slave ECDL. The self-feedback strength is adjusted by a piezo-disk in order to get the perfect Littrow configuration, and the coupling strength is adjusted using a polarizer. The feedback and coupling strengths are tuned so that the proportionate injection field to each laser is the same (= \eta). The path length between the lasers is 52.6 cm (coupled-cavity round-trip time = 3.5 ns). A fast avalanche photodiode (Hamamatsu C5331-02) is used to monitor the ECDL intensity, which is simultaneously recorded with a digital oscilloscope (Tektronix TDS350, resolution = 2.5 ns).

The experimental results of the LFPs from the ECDL with no coupling \eta = 0.0, and the amplitude suppression of these LFPs at a particular delay time (= coupled-cavity round-trip time) and varying coupling strengths, \eta = 0.0283, 0.0286 and 0.0311, are shown in figure 2.17. The figure clearly indicates that as we increase the coupling strength, amplitudes get suppressed. If we further increase the coupling strength \eta = 0.310 then slave laser shows periodic oscillations as shown in Fig. 2.18. The amplitude death state occurred at coupling
Figure 2.15: Photograph of the ECDL: external-cavity diode laser, TC: temperature controller, CC: current controller, G: grating, PZT: piezo-electric transducer, PBS: polarizing beam-splitter, POL: polarizer, PD: photo diode, PM: power meter, MC: monochromator, CVS: constant voltage source, LD: master laser diode, CA1, CA2: circular apertures, DT: digital thermometer

Figure 2.16: The schematic experimental set-up; ECDL: external-cavity diode laser, TC: temperature controller, CC: current controller, G: grating, PZT: piezo-electric transducer, PBS: polarizing beam-splitter, POL: polarizer, DU: detection unit, and OSC: oscilloscope
strength \( \eta = 0.324 \) as shown in Fig. 2.19. After this state, if we increase the coupling strength very high \( \eta = 0.526 \) then the slave laser goes to coherence collapse regime as shown in Fig. 2.20.

### 2.4 Route to ultimate amplitude-death state

In this work we find the three stages during the transition to complete amplitude death where the system gets stabilized as the coupling strength is increased from zero. We have seen two types of amplitude modulation of low-frequency complex dynamics in our coupled diode laser system depending on which type of coupling (self-feedback or injection) parameters dominates. For the optical self-feedback dominant case when \( \eta = 0 \), the ECDL (slave) shows the low frequency pulsations when biased close to threshold as shown in Fig. 2.17 (a). Physically, the high feedback light coupled back into the gain medium with delay. So gain saturation induced by the delayed feedback light causes the light in the cavity to receive a reduced amplification, consequently, after one round trip of feedback the population will be less depleted. As the field evolves further, the periodic oscillation of the gain build up, accompanied by the oscillating intensity of the light, which then has evolved into a low frequency periodic
Figure 2.18: Experimentally observed slave laser output powers (in microwatts) versus time (in seconds), showing periodic oscillation at injection strength $\eta = 0.310$ for a fixed time delay $= 1.75$ ns.

Figure 2.19: Experimentally observed slave laser output powers (in microwatts) versus time (in seconds), showing amplitude death with timer at injection strengths $\eta = 0.324$ for a fixed time delay $= 1.75$ ns.
pulsations (LFP). Now if we increase the \( \eta \) from zero then the ECDL shows the non-transient (LFF dynamics does not change with time) amplitude suppression with constant time delay as shown in Fig. 2.17 (b), 2.17 (c), 2.17 (d) at \( \eta = 0.0283, 0.0286, 0.0311 \) for fixed time delay \( \tau = 1.75 \) ns. If we further increase the coupling strength, then slave laser (ECDL) decreases the amplitude to death, but before getting the complete death state, this laser transition takes place to another dynamical state. At this transition point (at a particular coupling strength \( \eta = 0.310 \)) the ECDL lasing is quenched because the gain inside the laser to drop below the lasing threshold. In this second stage where injected ECDL shows the constant periodic dynamical output state as shown in Fig. 2.18. The reason is that the effective coupling constant in increased in magnitude in comparison to self-feedback constant and thus the force the gain medium to oscillate in the periodicity via Hopf bifurcation. Both coupling constants are opposite in sign leading to this Hopf-bifurcation to constant-periodic output, unlike the undamping of the relaxation oscillation period via Hopf bifurcation of the fixed point. At a constant time delay, the injection strength does not change the drop-out behavior (pattern or shape) except changing its amplitude. The change of oscillation amplitude with

Figure 2.20: Experimentally observed slave laser output powers (in microwatts) versus time (in seconds), showing coherence collapse at injection strengths \( \eta = 0.526 \) for a fixed time delay = 1.75 ns.
time depends on the relative phase between the oscillations of two lasers. In optical injection dominant case (optical injection greater than the optical feedback), the injected light does not meet the laser round-trip time phase condition, then, to a good approximation, we can assume that the amplified light only makes a single pass through the device before being lost from the laser cavity. This non-resonant amplification of light does not couple into the slave laser modes and decreases the carrier number density, results in increased refractive index and subsequently decreased cavity resonance frequency of the slave laser. In this third stage the amplitude decreases until ultimate amplitude death is established as shown in Fig. 2.19. If we further increase the coupling strength then the coherence collapse (CC) state is also observed experimentally at the $\eta = 0.526$ for $\tau = 1.75$ ns as shown in Fig. 2.20.

### 2.5 Conclusions

We have investigated the transition of the coupled diode laser system to ultimate amplitude death state by experimental observation. We have found [32] a new route to complete amplitude death in this purely optically coupled diode laser system. The different transitions are characterized in this way: low-frequency periodic pulsations → constant periodic motion → amplitude death state. The transition to complete amplitude death is manifested by two parameters: the coupling strength $\eta$ and coupled-cavity delay time $\tau$. The results presented in Fig. 2.17 show that for a small $\eta$ the amplitude does not reach zero in physically accessible time scales and complete amplitude death is not seen. However, for sufficiently large $\eta$, ultimate amplitude death could exist in a range of coupling strengths as shown in Fig. 2.19. Therefore, there exists a first stage which describes the process of transition to partial amplitude death and after that the laser jumps to another LFF state. At the onset of partial amplitude death, the master laser provides a sufficient delayed optical injection to the slave ECDL to suppress the LFF/LFP by destroying or pushing the antimodes far away from the external cavity mode, which are responsible for the power drop-out crisis. The injected light decreases the carrier density which results in an increase of the refractive index and subsequently a lowering of the cavity resonance frequency of the slave ECDL. The master laser provides a physical means to the slave ECDL for generating almost zero feedback through bi-directional coupling between the lasers. For very small injection strengths, both
the lasers are essentially independent and for large values of the injection strength, both the lasers are tightly coupled acting as one laser. At a particular set of values of $\eta$ and $\tau$ the laser transitions to amplitude death take place. An important advantage of this technique is that one can apply it, unlike most existing locking or stabilization technique, without changing any parameter of the ECDL.

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