PROBING THE DYNAMIC BEHAVIOUR OF RIDGE WAVEGUIDE MULTI-QUANTUM WELL DISTRIBUTED FEEDBACK LASERS: FUNDAMENTAL PICOSECOND STUDIES OF CHIRP UNDER LARGE-SIGNAL MODULATION

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science

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Abstract

Probing the Dynamic Behaviour of Ridge Waveguide Multi-Quantum Well Distributed Feedback Lasers: Fundamental Picosecond Studies of Chirp under Large-Signal Modulation

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Thesis submitted in conformity with the requirements for the degree of Master of Applied Science
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This work presents the first experimental report of time-resolved measurement of directly-modulated telecommunications-wavelength lasers at 1310 nm using a double subtractive monochromator combined with streak camera. This work combines in a novel manner the picosecond and potentially sub-picosecond temporal resolution of the streak camera with the sub-Angstrom wavelength resolution of the double-subtractive monochromator without undue temporal distortion. The 0.05 nm resolution of the double subtractive monochromator and 12 ps temporal resolution of the streak camera were used to observe the detailed profile of transient chirping over excursions of 0.08 nm and 0.1 nm in directly modulated lasers. Measurement of the spectro-temporal evolution of laser emissions under these conditions is of critical importance in enabling metropolitan-area and regional networks based on cost-effective source technologies. The novel experiment reported herein provides a wealth of information compared to broadly-applied methods of measuring laser evolution based on fast photodetectors and wavelength discriminators.
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Chapter 1

Motivation, Literature Review, and Objectives

1.1 Motivation: Studying the Semiconductor Laser

Optical fiber plays a key role in increasing the bandwidth of the telecommunication network. The best performance of optical fiber is obtained using transmitted light of wavelength around 1.3 μm where the dispersion is zero, or 1.55 μm where the loss is minimum. Transmitting information by modulating the current driving a semiconductor laser provides a simple, single-component solution to putting data onto the optical carrier. Lasers with narrow linewidth and high modulation bandwidth emitting at 1.3 μm and 1.55 μm are urgently required as a result.

Multi-quantum well semiconductor lasers (MQW) are promising candidates for medium-haul, or regional, optical networks due to their high optical gain and differential gain and their low threshold current. Multiple frequency sources will introduce a large power penalty, necessitating development of single frequency lasers. Distributed feedback lasers (DFB) are realized by adding a longitudinal grating near active layer. The grating produces frequency-selective backreflection, favouring lasing of a single longitudinal mode. Two types of DFB laser are available: gain-coupled and index-
coupled. Gain-coupled DFB lasers have been demonstrated to have many advantages over index-coupled DFB lasers, including high single-mode selectivity, less sensitivity to external reflections, reduced wavelength chirp, narrower linewidth, larger TE/TM mode discrimination, and lower threshold currents. Strained-layer MQW active regions have been predicted to facilitate higher bandwidth than lattice-matched MQW laser due to their enhanced differential gain. There remain challenges, however, in achieving high modulation bandwidth, often attributable to high damping factor and carrier transport effects [7]. A schematic cross-section of a DFB laser with a ridge waveguide structure (RWG) and etched quantum wells is shown in Figure 1.1. Show in Figure 1.2 is a longitudinal grating formed in the lower cladding layer.

![Schematic cross-section of a 1.3 μm strained MQW gain-coupled DFB laser with RWG structure](image)

Figure 1.1 Schematic cross-section of a 1.3 μm strained MQW gain-coupled DFB laser with RWG structure [16].
There remain unsolved problems which have a direct negative impact on DFB laser performance. These include current leakage, heating, nonuniform carrier distribution among the multiple quantum wells, and frequency chirp. Current leakage worsens the threshold current and lowers the lasing efficiency, though its origins are various and not always easily isolated. Nonuniformity in the distribution of carriers among the wells of a multiple quantum well (MQW) laser has been recognised in the 1990’s as an important mechanism in determining threshold, efficiency, modulation bandwidth, and chirp.

1.2 Motivation: Studying Dynamic Laser Behaviour

Although static lasing characteristics provide important information, laser behaviour under direct, high-speed modulation also requires detailed investigation. The change in the lasing spectrum during modulation as well as limits on the modulation bandwidth demand careful attention to the dynamic behaviour.
In existing optical transmitters, the optical power emitted by the semiconductor laser is modulated by applying a time-varying current; or, alternatively, the laser is operated in continuous-wave mode and the optical carrier is subsequently modulated using an external modulator. The external modulator must be coupled with the DFB laser, increasing the cost of packaging considerably. The external modulator achieves higher performance by permitting control over frequency chirp. Direct modulation of the semiconductor laser has the advantage of being more cost efficient – an increasingly important consideration in metropolitan and regional networks.

It has been found that the optical intensity modulation can follow the current modulation up to frequency near to the relaxation frequency. The study of dynamic characteristics such as resonance frequency and damping factor is of central importance in assessing the potential of a laser for use in directly-modulated applications.

Additionally, direct modulation of DFB lasers causes fluctuation in the wavelength of laser light. This phenomenon is known as frequency chirp. When the laser current is increased, the carrier density grows, which will reduce the index of refraction and will shift the wavelength to the blue. The same effect will produce a shift of the wavelength to red when the current is decreased. The red and blue shift of the pulse imply a broadening of the spectrum of the pulse. As a result of dispersion, the broadened pulse will spread more rapidly and the resulting intersymbol interference will increase the bit error rate. A method of accurate characterisation of the frequency chirp is necessary to optimise the performance of fiber-optic communication systems.
1.3 Literature Review

Three methods for real-time measurement of the dynamic behaviour were developed up to 1984: second harmonic correlation (SH), up-conversion, and ultrafast-response photodetector with oscilloscope. Although SH correlation can reach subpicosecond time resolution, the measured data provide only indirect information on the pulse shape and width. The up-conversion technique gives direct information but high laser power is necessary. With an ultrafast oscilloscope the time response is limited by the photodetector and oscilloscope bandwidth.

Onodera et al. reported a real-time measurement of ultrashort optical pulses from an InGaAsP diode laser using an ultrafast streak camera combined with nonlinear optical up-conversion technique [17]. The single pulse at 1.3 µm wavelength from the laser diode was up-converted by another pumping laser beam Q-switched Nd:YAG laser at 1.064 µm through a LiNiIO₃ nonlinear crystal to generate a signal at the sum-frequency for which the sensitivity of the streak camera is high.

Bimberg et al. generated 4 ps pulses at 840 nm at repetition rates up to 10 MHz by directly modulating GaAlAs-V-groove lasers using a specially designed double avalanche transistor circuit [1]. The avalanche circuit is triggered directly by a pulse generator. The optical pulses generated were measured using a Hamamatsu C1370 single-shot streak camera.

The group of Tsang at AT&T Bell Laboratories reported measurement of a temporal waveform and time-averaged spectrum of a 1.5 µm gain-coupled InGaAsP/InP DFB laser using a synchroscan streak camera and optical spectrum analyser (OSA) [2]. They did not report measurement on time-wavelength spatial map.
The direct time-resolved waveform of a 1.3 \( \mu m \) MQW InGaAsP laser was obtained using a synchroscan streak camera by Tsuchiya et al. in 1985 [3]. Further developments of this technique and application of time-resolved spectroscopy to 1.5 \( \mu m \) a InGaAsP laser diode were reported later that year by the same Tsuchiya et al. [4]. A pulse broadening of 26 ps due to the streakoscope was observed in both papers.

More recently, Sogawa and Arakawa studied picosecond lasing dynamics of gain-switched GaAs-AlGaAs MQW lasers using time-resolved spectral measurements. A C1837 Hamamatsu streak camera combined with a monochromator was used to resolve ultrafast lasing dynamics manifested in short pulses generated by gain switching [5]. The results revealed broadening of the pulse spectral width. These results were for lasers producing light at 850 nm, a wavelength shorter than those used in metro and long haul communication systems. Light is much easier to detect in a streak camera at this wavelength in view of the orders of magnitude higher photocathode sensitivity. In the infrared region, which corresponds to low photon energy, the thermal noise becomes important and degrades the sensitivity of the photodetector.

Wada et al. studied chirp in a multimode laser emitting at 800 nm [6]. This was obtained using time-resolved spectral measurements using a Hamamatsu C4334-02 streak camera combined with a spectrometer.

The variation of the spectral chirp with bit rate and bias conditions was studied by Lu in [7]. He obtained time-averaged spectra for a partly gain-coupled 1.55 \( \mu m \) DFB laser using an optical spectrum analyzer. The modulation bandwidth was derived from the small signal frequency response; the resonance frequency, the damping factor and differential gain were obtained from relative intensity noise (RIN) measurements.
In optically time-division multiplexed (OTDM) transmission systems, repetition rates of hundreds of gigahertz are used whereas the maximum repetition rate of a typical streak camera is 160 MHz. The optical pulses generated at such ultrahigh-bit rates are not synchronised with any available electrical reference. Katagiri and Takada used a phase-locked loop for synchronising a passively mode-locked semiconductor laser to an electrical signal [8]. In this way the authors synchronised a mode-locked signal at 36.6 GHz with an 80 MHz synchroscan camera for the first time.

1.4 The Work: A New Experimental Approach

A review of the literature reveals that streak camera combined with a spectrometer provides an attractively direct means of studying laser dynamic behaviour. In previous studies of this nature, however, the spectrometer induced a significant broadening of the pulse, degrading the temporal resolution with which a useful measurement could be acquired. Moreover, widely available streak cameras suffer from very poor sensitivity at telecommunication wavelengths 1.3 μm and 1.5 μm.

In the present work, a double-subtractive monochromator is used in combination with a streak camera sensitized for 1.31 μm operation. The double subtractive monochromator is used to eliminate dispersion in time, which occurs in previously-reported single-grating results.

The laser studied in the present work is a 1310 nm DFB gain-coupled ridge waveguide MQW InGaAsP-InP device. Time resolved spectra are obtained for a laser under direct modulation. This work presents for the first time the use of a streak camera
in combination with a double-subtractive monochromator to study the time-resolved spectral behaviour of 1.3 and 1.55 μm DFB lasers designed for 10 Gbps modulation.

1.5 Organisation of Thesis

In Chapter 2, to provide a physical basis for interpreting novel measurement results, analytical solutions are developed for carrier and photon dynamics under small signal laser modulation. Results of numerical analysis for large-signal modulation and a description of the mechanisms limiting bandwidth and creating frequency chirp are also presented. Chapter 3 describes the laser device and laser package used for measurements. Chapter 4 describes the experimental set-up used for static and dynamic measurements. The results and analysis of the measurements are presented in Chapter 5. Conclusions and future directions are presented in Chapter 6.
Chapter 2

Physical Mechanisms of Semiconductor Laser Operation

2.1 Introduction

The distributed feedback lasers mentioned in the previous chapter are aimed at 10 Gbps directly-modulated applications. To achieve modulation bandwidths in this vicinity with acceptable frequency chirp is a significant challenge. Before these specifications can be met, it is first necessary to understand which physical phenomena will dominate and limit laser performance. Knowledge of processes at work inside the laser will allow design and tailoring to meet both present and future application requirements.

2.2 Physics of Dynamic Behaviour under Small Signal Modulation

2.2.1 Basic Theory

Modulation of the current injected into the laser results in a modulation of both carrier density $N$ and photon density $N_p$. The modulation of the carrier density changes
the gain and the active region refractive index \( n_a \). The optical length of the laser is thus modulated by the current, causing a change in the resonant frequency. To model mathematically the operation of semiconductor laser, coupling between photons and electrons population must be taken into account. The rate of absorption and emission of photons, along with the rate of recombination/generation of electrons and holes, provides particle and energy conservation [9].

The rate of change of number of photons inside the laser cavity \( V \) is given by [9]:

\[
\frac{d(VN_p)}{dt} = (v_g g N_p)\Gamma V - \frac{N_p V}{\tau_p} + \beta_{sp} R_{sp} \Gamma V; \tag{2.1}
\]

Where \( v_g \) is the group velocity, \( \tau_p \) is the photon lifetime, \( N_p \) is the total number of photons, \( V \) is the active layer volume, \( g \) is the material gain, \( R_{sp} \) is the rate of spontaneous emission, \( \beta_{sp} \) is the spontaneous emission factor and \( \Gamma \) is the modal confinement factor. The first term of Equation (2.1) gives the rate of stimulated emission of photons as a result of nonequilibrium electrons within the laser's active region. The confinement factor \( \Gamma \) accounts for the fraction of the optical mode that is inside the gain region of volume \( \Gamma V \), where \( V \) is the total cavity volume and \( g \) represents the optical amplification per unit length. The second term represents the optical power loss per unit time by absorption or escape from the cavity through the laser facets. The final term quantifies spontaneous emission of photons. Only a fraction \( \beta_{sp} \) of the spontaneous recombination rate is included because only those photons which are guided by the laser waveguide are retained inside the cavity. When the laser is lasing strongly, this last term may be neglected.
The rate of change the number of electrons $N$ inside the active region of volume $\Gamma V$ is given by [9]:

$$\frac{dVN}{dt} = \frac{\eta_i I}{q} - \frac{R_{sp} + R_{nr}}{V} - V V g_{N_p}$$  \hspace{1cm} (2.2)

The first term accounts for the fact that only a fraction $\eta_i$ of the carriers injected through the contacts actually reach the active region. The term is known as the injection efficiency for the laser. This current injected into the active region is the source of electrons which balance the net rate of loss of electrons caused by all forms of recombination. The second term quantifies spontaneous and nonradiative recombination. The third term gives the rate of removal electrons by stimulated recombination required to produce material gain $g$.

The parametric dependence of gain on carrier density and photon density is expressed by [9]:

$$g(N, N_p) = \frac{g_0}{1 + \varepsilon N_p} \ln \left( \frac{N + N_z}{N_{tr} + N_z} \right)$$ \hspace{1cm} (2.3)

Taking in account the nonlinear dependence of gain on photon by the gain compression coefficient $\varepsilon$ is very important in interpretation of the experimental results. The gain compression factor varies on different laser structure and material. Higher gain compression factor are found in strain DFB laser. Spectral hole burning and hot carrier and horizontal carrier diffusion in the plane of the layers are the main effect which are responsible for a high compression factor. An additional term $N_S$ is added for fitting of the gain equation with the gain curve for various types of laser active region.
The differential gain \( dg \) is affected by both carrier and photon density variation as shown in Equation (2.4) [9]. The signs reflect the fact that gain increases with increasing carrier density and decreases with increasing photon density.

\[
dg = a_dN - a_p dN_p
\]  

(2.4)

where the gain derivatives are:

\[
a_d = \frac{\partial g}{\partial N} = \frac{g_0}{(N + N_s)(1 + \varepsilon N_p)} = \frac{a_0}{1 + \varepsilon N_p}
\]  

(2.5)

\[
a_p = -\frac{\partial g}{\partial N_p} = \frac{\varepsilon g}{1 + \varepsilon N_p}
\]  

(2.6)

The term \( a_0 \) is defined as the nominal differential gain when the photon density is zero.

To analyse the dynamic behaviour of a laser in response to current modulation, the rate equations should be evaluated in time domain. A good approximation for small signal modulation is to consider a small perturbation from the steady state. The differential of both rate equations (2.1) and (2.2) is written as [9]:

\[
\frac{d}{dt} \begin{bmatrix} dN \\ dN_p \end{bmatrix} = \begin{bmatrix} -\gamma_{NN} & -\gamma_{NP} \\ \gamma_{PN} & -\gamma_{PP} \end{bmatrix} \begin{bmatrix} dN \\ dN_p \end{bmatrix} + \frac{\eta_e}{qV} \begin{bmatrix} dt \\ 0 \end{bmatrix}
\]  

(2.7)

where the matrix coefficients are defined by the following relation:

\[
\gamma_{NN} = \frac{1}{\tau_{\Delta N}} + v_g a N_p, \quad \gamma_{NP} = \frac{1}{\Gamma \tau_p} - \frac{R_{sp} \beta_{sp}}{N_p} - v_g a_p N_p
\]

(2.8)

\[
\gamma_{PN} = \frac{\Gamma}{\tau_{\Delta N}} + \Gamma v_g a N_p, \quad \gamma_{PP} = \frac{\Gamma R_{sp} \beta_{sp}}{N_p} + \Gamma v_g a_p N_p
\]

where \( \tau_{\Delta N} \) is the differential carrier lifetime given by [9]:

\[
1/\tau_{\Delta N} = dR_{sp}/dN + dR_{nr}/dN
\]  

(2.9)
$1/\tau_{AN}$ is proportional with the local slope of the spontaneous and nonradiative rates ($dR/dN$), in contrast with $1/\tau_N$ (which is proportional with the overall slope $R/N$). $\tau_{AN}$ is the differentiatial lifetime of carriers which radiate photons into the lasing mode through spontaneous emission and is negligible for a laser dominated by stimulated emission.

### 2.2.2 Analytical Solution for Small Signal Modulation

An analytical solution has been developed to the above equations by Coldren and Corzine [9] for small signal perturbation. Solutions for large signal modulation are only obtainable by numerical solution. For a single-mode laser and sinusoidal current modulation, the perturbation of current carrier and photon density can are very small and can be approximated by [9]:

\[
\begin{align*}
    dI(t) &= I_1 \exp(j\omega t), \\
    dN(t) &= N_1 \exp(j\omega t), \\
    dN_p(t) &= N_p \exp(j\omega t),
\end{align*}
\]  

(2.10)

Solving the system of Equations (2.7) combined with the boundary condition from Equation (2.10), carrier and photon densities may be expressed as [9]:

\[
\begin{align*}
    N_1 &= \frac{\eta I_1}{qV} \frac{\gamma_{pp} + j\omega}{\omega^2_R} \cdot H(\omega) \quad (2.11) \\
    N_{p1} &= \frac{\eta I_1}{qV} \frac{\gamma_{pn}}{\omega^2_R} \cdot H(\omega)
\end{align*}
\]

where $H(\omega) = \frac{\omega^2_R}{\omega^2_R - \omega^2 + j\omega\gamma}$ is the modulation transfer function, $\omega_R$ is the relaxation oscillation frequency, $\gamma$ is the damping factor. The relaxation resonance frequency and
damping factor have the following associations with the terms described in Equations (2.8) [9]:

\[
\omega_R^2 = \gamma_{NP\dot{\gamma}_{PN}} + \gamma_{PP\dot{\gamma}_{NN}}
\]

\[
\gamma = \gamma_{PP} + \gamma_{NN}.
\]

The intensity modulation follows the current modulation up to the relaxation frequency. Beyond resonance, the response drops off dramatically. The peak frequency of the resonance is slightly less than \(\omega_R\) depending on damping factor \(\gamma\). The relaxation frequency can be increased by increasing the photon density. This continues until the photon density approaches \(1/e\), at which point the differential gain begins to fall off due to gain compression.

\[
H(\omega) \text{ may be written as a product of two single-pole transfer functions [9]:}
\]

\[
H(\omega) = \frac{\omega_R^2}{(j\omega + s_1)(j\omega + s_2)}
\]

where the complex roots are:

\[
s_{1,2} = \frac{1}{2} \gamma \pm j\omega_{asc} \text{, } \omega_{asc} = \omega_R \sqrt{1 - (\gamma / 2\omega_R)^2}
\]

In Equation (2.16), \(\omega_{asc}\) is the frequency at which photon and carrier density will oscillate before they decay to a steady-state value with decay characterised by the damping factor \(\gamma\).

The complex roots \(s_{1,2}\) from Equation (2.16) suggest solutions of the following form [9]:

\[
e^{-\gamma/2}(e^{j\omega_{asc}/2} \pm e^{-j\omega_{asc}/2})
\]
Equation (2.16) provides a general form of the transient response to a sudden increase in the current by $dI$, named $dN(t)$ and $dN_p(t)$ [9]. The effect on photon and carrier density is given by [9]:

$$dN(t) = dN_0 e^{-\gamma t/2} \sin \omega_{osc} + \frac{a_p}{a} dN_p(t) \tag{2.18}$$

$$dN_p(t) = dN_p(\infty)[1 - e^{-\gamma t/2} \cos \omega_{osc} t - \frac{\gamma}{2\omega_{osc}} e^{-\gamma t/2} \sin \omega_{osc} t] \tag{2.19}$$

where final values of carrier and photon density are:

$$dN(\infty) = \frac{\eta L dI}{qV} \Gamma \tau_p \frac{a_p}{a} \tag{2.20}$$

$$dN_p(\infty) = \frac{\eta L dI}{qV} \Gamma \tau_p \tag{2.21}$$

$$dN_0 = \frac{\eta L dI}{qV \omega_{osc}} \tag{2.22}$$

Equations (2.18) and (2.19) are valid as long as the perturbation is small compared to steady state carrier and photon densities.

### 2.3 Large Signal Modulation

To determine the dynamic response of the laser under large-signal modulation, a numerical approach is required in view of the nonlinear nature of the coupled rate equation system. The temporal evolution of $N$ and $N_p$ calculated numerically for an InGaAsP Fabry-Perot laser is given for example in Agrawal [2].

The response under large signal modulation exhibits turn-on delay, rise time, overshoot damping, and oscillations in the transient response. The large signal response of the main and the side mode for a Fabry-Perot laser is illustrated in Figure 2.1. A small
variation in carrier density induces a large variation in the photon density. The damping of the side modes is much higher than the main mode, and therefore reaches a steady state much faster. In contrast, in a DFB laser the optical power contained in the side modes is much smaller than in the main mode and is usually neglected.

![Image](image_url)

**Figure 2.1** Time evolution of the carrier density and output power of a Fabry-Perot laser in response to a large signal step current of finite duration [14].

An analytical expression for the photon and carrier rates for large-signal modulation has been developed by Carroll and Whiteaway [15]. For DFB lasers, numerical solution is required because the phasing, nonuniform fields, and distribution of the feedback are very significant [15]. Approximate analytical expressions nevertheless assist in developing some qualitative understanding of the temporal characteristic of the DFB laser.

The simulated performance for a DFB laser with significant delay (~70 ps) in injecting carriers in active regions is illustrated in Figure 2.2. Turn-on is shown in Figure 2.2.a while Figure 2.2.b shows the variation of the main and side mode wavelengths.
Based on simulation, the chirp is evaluated to be less than 2 Å. Simulation results shown in Figure 2.3 c gives a 45 dB side mode suppression ratio. Simulated time-averaged spectrum for spectrum analyser with an optical resolution bandwidth of 0.1 nm is presented in Figure 2.3 e.

Figure 2.2 Simulated performance of a $2x\lambda/m/8$ DFB laser. (a) Total intensity vs. time; (b) Wavelength of each mode vs. time; (c) Power in each mode vs. time; (e) Time-averaged spectrum [15].
2.4 Mechanisms Limiting High-Speed Lightwave Systems Based on Directly Modulated Lasers

2.4.1 Modulation Bandwidth

The amplitude modulation response of a directly modulated laser is given by [9]:

\[
\frac{P_i}{I_i} = \eta_i \eta_o \frac{hv}{q} H(\omega)
\]  \hspace{1cm} (2.23)

where the transfer function is given in Equation [2.15]. It has been found that the intensity modulation can follow the current modulation up to frequency near \( \omega_R \) and drops sharply for modulation greater than \( \omega_R \). The actual peak frequency of resonance \( \omega_p \) is slightly less than \( \omega_R \) depending on damping factor \( \gamma \).

The relation between damping factor and relaxation frequency is given by Equation (2.24) [9]:

\[
\gamma = K \omega_R^2 + \gamma_0.
\]  \hspace{1cm} (2.24)

where \( K \) describes the damping of the response and it is an important parameter in characterisation of high speed lasers.

When \( \gamma/2\omega_R << 1 \), the system is underdamped and the oscillation are characterised by the relaxation resonance frequency \( \omega_R \). Since the damping factor is proportional with the square of relaxation frequency, Equation (2.24), which increases with photon density, increasing the power, increases not only \( \omega_R \) but also \( \gamma \). Near critical damping, when \( \gamma/2\omega_R \rightarrow 1 \) and \( \omega_{osc} \rightarrow 0 \), the photon density will simply rise/fall exponentially to its new steady-state value.
The simulation of the variation in time of the carrier density for different gain compression factors is presented in Figure 2.3. The oscillations in carrier density are damped much faster or even disappear with a high compression factor. The carrier density is higher for a higher compression factor and the rise time is increased as shown in Figure 2.3.

![Figure 2.3. Simulated carrier density variation in time for the current step of 2xI_th for different initial currents and different gain compression factors. Solid line: bias current 1.5xI_th and no gain compression; red dashed line: bias current 1.001xI_th and gain compression factor ε=1x10^{-23} m^3; green dotted line: bias current of 1.5xI_th and gain compression factor ε=1.75x10^{-22} m^3.](image)

Results for photon density as a function of time are shown in Figure 2.4. The effect of damping is much stronger when the laser is biased above threshold than when the laser is biased close to threshold.
When the system is overdamped, $\gamma/2\omega_R > 1$, the oscillation frequency becomes imaginary and the response is slower as seen in Figure 2.4. The maximum modulation bandwidth is obtained when $\gamma/2\omega_R = 1/\sqrt{2}$ which results in oscillations at frequency $\omega_{osc} = \omega_R/\sqrt{2}$.

![Figure 2.4. Simulated temporal output power variation with different gain compression factors when the current is increased from 1.5x$I_{th}$ to 3.5x$I_{th}$. Blue solid line: no gain compression; cyan dotted line: $\varepsilon=1\times10^{-23}$ m$^3$; red dashed line: $\varepsilon=0.5\times10^{-22}$ m$^3$; black solid line: $\varepsilon=1.75\times10^{-22}$ m$^3$.](image)

The modulation bandwidth, $\omega_{3db}$, is defined as the frequency at which the electrical response drops at half of its dc value. The modulation bandwidth for low damping, as well as the maximum possible bandwidth, is given by the Equations (2.25) and (2.26) [9]:

$$f_{3db} = f_R \sqrt{1 + \sqrt{2}} \quad (\gamma/\omega_R << 1) \quad (2.25)$$
\[ f_{3dB|_{\text{max}}} = \sqrt{2} \frac{2\pi}{K} \quad (\gamma/\omega_R = \sqrt{2}) \]  

(2.26)

From the above relations it can be observed that modulation bandwidth increases linearly with the relaxation resonance frequency in the case of underdamping. At strong damping, the bandwidth decreases with further increase in \( \omega_R \). Optimum damping and maximum bandwidth occur when \( \omega_R = \gamma/\sqrt{2} \) and \( \omega_R = \omega_{3dB} \).

2.4.2 Frequency Chirp

The material susceptibility is a function of carrier density \( N \), carrier temperature \( T_c \), photon density \( N_p \), and lattice temperature \( T_L \). Any variation of these parameters induces variation of index of refraction and gain coefficient and, consequently, a change in the lasing wavelength.

Current modulation will induce carrier density modulation, which leads to frequency modulation that broadens the spectrum of the laser as it can be seen in Figure 2.3 b and e.

Linewidth Enhancement Effect

The real and imaginary components of the index of refraction are affected by the carrier density \( N \) as described using the linewidth enhancement factor [9]:

\[ \alpha = \frac{dn/\lambda dN}{dn/\lambda dN} - \frac{4\pi}{\lambda} \frac{dn/dN}{dg/dN} \quad (2.27) \]

When the current applied to the laser changes, the gain changes and therefore, by Equation (2.27), the refractive index is changed:

\[ \Delta n = -\alpha \Delta g/2\pi \]  

(2.28)
The relation $v_n L = mc/2$ describes the longitudinal mode frequencies $v$ of a Fabry-Perrot laser. Differentiation of this relation with respect to carrier density and frequency, gives the result:

$$\Delta v_n + v \frac{dn}{dN} dN = 0$$  \hspace{1cm} (2.29)

A general relation of the frequency chirp $\Delta v$ is then obtained [9]:

$$\Delta v = -\frac{\Gamma v}{\lambda} \frac{dn}{dN} \Delta N.$$  \hspace{1cm} (2.30)

If the linewidth enhancement factor $\alpha$ is introduced, frequency chirp may be written:

$$\Delta v = -\frac{\alpha}{4\pi} \Gamma v \alpha \Delta N.$$  \hspace{1cm} (2.31)

The frequency chirp is proportional to the linewidth enhancement factor, the differential gain, the carrier density change.

The Equation (2.32) is used in the experimental measurement of carrier heating at modulation frequency around 100 MHz. Using the photon density rate equation (2.1) and (2.31) the frequency chirp is given by the relation [9]:

$$v - v_{th} = \frac{\alpha}{4\pi} \left( \frac{1}{N_p} \frac{dN_p}{dt} - \frac{\Gamma R_{wp}}{N_p} + \Gamma v \alpha a p N_p \right)$$  \hspace{1cm} (2.32)

For large signal modulation, Equation (2.32) gives the magnitude of the frequency chirp for modulation frequency above 10 MHz. Above 10 MHz, the thermal effects are negligible and Equation (2.32) is in concordance with experimental results. The second term in Equation (2.32) is small and may be neglected. The third adiabatic term from Equation (2.32) depends mostly on the optical power and is the dominant term.
at low modulation frequency and high photon density, and it is related to the damping relaxation oscillation.

For very fast modulation (at the order of GHz), the frequency chirp $\Delta v = v - v_{th}$ is reduced to the first term which is dominant. This can be written in another form, Equation (2.33), which gives the dependence of the chirp on a more tangible parameter optical power, $P(t)$ which is proportional with the photon density.

$$\Delta v = \frac{\alpha}{4\pi} \left( \frac{d \ln P(t)}{dt} \right)$$

(2.33)

The Effect of Heating

Heating, which can occur over various time scales, changes many key internal laser parameters, including injection efficiency, refractive index, gain spectrum, and carrier density dependence. Heating implies not only lattice heating but also carrier heating – an effect that may become particularly pronounced under high frequency modulation and are one of the factor which cause a high damping factor. In this case, electrons and holes may not have enough time to equilibrate with the lattice, resulting in a difference in temperature between carriers and the lattice. The hot electrons have enough energy to pass through the wells without recombining. Device (lattice) heating is significant when the modulation frequency is below 10 MHz. Carrier heating dominates for modulation above 100 MHz.

The change of the refractive index and gain due to temperature variation will introduce chirp as well. Thermal chirp due to the lattice heating occurs at modulation frequency bellow 100 MHz.
2.5 Conclusion

In the present chapter, the theoretical basis underlying many aspects of the design and analysis of semiconductor lasers were presented. The theory and simulations presented herein provide a helpful basis for interpretation the experimental results at the heart of the novelty of the present work.

In the next step, the packaged laser used for measuring the chirp with the new experimental set-up will be investigated in detail.
Chapter 3

Devices under Test

3.1. Introduction

In the present chapter, a detailed description is provided of the laser whose behaviour forms the focus for this work. The laser studied is a gain-coupled DFB ridge-waveguide laser emitting at 1310 nm.

3.2 InGaAsP-InP DFB Gain-Coupled Ridge-Waveguide Laser

The schematic cross-section of a 1310 nm InGaAsP-InP strained MQW gain-coupled laser is shown in Figure 1.1.

In contrast with the FP laser, the DFB laser employs an etched grating on one of the cladding layers or the active region. The choice of grating period is governed by the desired lasing wavelength in the medium and the order of the Bragg diffraction used for distributed feedback.

There are two types of DFB laser: index-coupled and gain-coupled. As it was explained in the first chapter, and proved experimentally [2, 7, 14,16], gain-coupled DFB lasers are preferable to index-coupled DFB lasers. Etching of the active layer in gain-coupled DFB laser does present the disadvantage of increasing nonradiative recombination by introducing defects within the active region. Gain-coupled lasers with
the grating inside the active region provide a very high modulation bandwidth of 22 GHz as reported by H. Lu [7].

3.3 Packaged Laser

The DFB laser studied in the present work is packaged as shown in the microscope image of Figure 3.1. Items include the laser, a photodetector, a thermistor, a resistor for impedance matching with RF cable, a thermoelectric cooler, a ball lens, optical isolator and fiber pigtail. The temperature inside the laser can be controlled by applying a bias between pins 6 and 7 which provides current to the thermoelectric cooler.

![Figure 3.1 View inside the packaged laser. 1 Photodetector; 2 RF choke, 3 Laser, 4. Ball lenses, 5. Heat sink, 6. Optical isolator, 7. 45 R_{match}, 8 R_{thermistor}.](image)

The thermistor measures the heatsink temperature and is used to provide feedback to the temperature controller in order to keep the laser at a constant temperature. Slow variations in the optical power can be detected by measuring the light from the back facet using the monitor photodiode (pins 4 and 5). The use of an optical isolator is necessary
due to the high sensitivity of the laser to backreflections. Also, to avoid backreflection, the monitor photodiode is angled to respect to laser axis and AR coated.

The electrical diagram of the DFB laser is given in Fig. 3.2. For continuous characteristics a DC bias is applied between pin 3 and ground. When the laser is modulated, the RF input is combined with a SMA (Subminiature A) cable using GPO connector (small profile Gilbert) designed for modulation frequency up to 40 GHz. A 45 Ω resistor in series with the RF line is used to match the 50 Ω impedance of the cables. The RF choke which behaves as an inductor, is a low pass filter which allowed pass only DC current.

![Diagram](image)

**Figure 3.2 Electric Diagram [After Nortel laser data sheet].**

Figure 3.3 is a picture of the 1.3 μm DFB laser with GPO connector.
3.4 Conclusions

The components inside the gain-coupled DFB RWG packaged laser are described in this chapter. Laser packaging is an important determinant of the stability of the laser to temperature and environment, and enables ready connection into the optical network or, in the case of the present work, into the experimental measurement system.

In the next chapter the experimental apparatus used to characterize the packaged laser is presented.
Chapter 4

Experiment

4.1 Static Measurements

The final aim of the present work is to observe through direct, novel measurement the dynamic behaviour of a buried heterostructure laser under direct modulation. In anticipation of later studies of chirp, it is necessary first to study the steady-state spectral behaviour at the “0” and “1” bias points between which the laser will be modulated.

Knowledge of the current at which the laser reaches threshold is needed to choose the right bias during direct modulation experiments. For direct modulation the laser is kept above threshold at all times in order to obtain a fast response. Knowledge of the slope efficiency per facet will guide expectation as to the arrival rate of photons expected in the streak camera in dynamic studies.

An Avtech AV-155A-B current source is used to inject current into the laser. The laser optical output is connected to a Ge detector through a fiber-optic adapter that prevents overfill effects. Due to the divergence of the beam, the spot could be larger than the photodetector area were it not for the collimating optics employed herein. The Newport 1830-C power meter is used to measure the laser optical power at different currents by measuring the optical power incident on the Ge photodetector with high
efficiency in the infrared wavelength region. The current source and power meter are controlled via a GPIB interface. L-I data are extracted using a LabVIEW program.

![Diagram](image)

**Figure 4.1 Experimental Set-up for L-I curve.**

Knowledge of the relationships between applied voltage and the resulting current through the laser is later used in the selection of parameters for the time-averaged spectral measurements described in Section 5.2.1. The bias generated using the Keithley 228A voltage source is applied to the DC input pin of the laser.

The spectrum of light produced by the laser was measured using an optical spectrum analyser (OSA). Because the DFB laser has a narrower linewidth than the spectral resolution of the OSA, the measured linewidth of an unmodulated laser is in fact dominated by the instrument rather than the laser spectrum itself. The HP 70004A OSA was used to obtain the spectrum.
4.2 Dynamic Measurements

Three types of dynamic measurements are made in the present work: time-averaged spectra, time-resolved profile, and time-resolved spectra. The experimental set-up used in each case is described below.

4.2.1 Time-Averaged Spectra

Some information about chirp from the laser may be gained by measuring the broadening of the spectrum averaged over time. Spectral characteristics measured under different sinusoidal direct current modulation conditions at various frequencies, amplitudes, and bias conditions may provide information regarding averaged chirp broadening.

Time-averaged spectra are recorded using the optical spectrum analyser. The sinusoidal modulation frequency was varied between 0.1 MHz and 990 MHz. A modulation voltage between 2 and 3 Volts was employed, providing a current modulation between 40 and 60 mA. This corresponds to a peak-to-peak current swing of $1.5 I_{th}$.

Laser biasing is usually thought of in terms of injected current instead of voltage; however, a current source cannot be used in combination with a signal generator to obtain a modulation with a specific DC bias. The 45 $\Omega$ resistance connected in parallel with the laser is not an open circuit, as when current is injected through pin 3, and most of the current will pass through the resistor instead of the laser [Fig. 3.2]. A voltage source must instead be used as separate DC bias source. The voltage source is connected through pin 3 to provide the DC input. To generate the electrical modulation shape desired, a DC
voltage generated using the Keithley 228A voltage/current source is combined to the AC sine-wave voltage generated by HP 8656A signal generator. The voltage generated by signal generator is applied through the RF input. This experimental set-up is used in obtaining the measurements which are reported in Chapter 5, Section 5.2.1, later in this work.

4.2.2 Time-resolved measurements

To reveal the temporal behaviour of the optical emissions from the laser under study during the turn-on and turn-off transients, a Hammamatsu C5680 synchroscan streak camera is used.

The streak camera has a low efficiency in the IR region due to the low sensitivity of the photocathode in this region. The photocathode used is a S1 type.

The operation of the streak camera is described below and is illustrated in Figure 4.2. Incident light is projected onto the photocathode of the streak tube using a system of lenses. Photons are transformed in electrons at photocathode, are accelerated and multiplied by micro channel plate (MCP), and are swept along a vertical axis by deflecting plates whose voltage varies in time. The high-speed sweep voltage applied to the plates ensures that electrons arriving at different times during the sweep will arrive at different locations on the phosphor screen. Each vertical point on phosphorous screen therefore corresponds to a certain voltage of the deflection plate and, correspondingly, a particular point in time. The temporal resolution which can be obtained using the streak camera employed in the present work is at best 2 ps. The resulting beam of electrons is converted back into light by the phosphor screen. The result is imaged using a CCD.
camera. The signal generator provides a periodic voltage sweep (synchroscan) to which the pulse generator driving the laser is synchronised.

![Schematic diagram of streak camera components.](image)

**Figure 4.2 Components of streak camera.**

The Avtech AVNN-1-C voltage pulse generator is used to drive the laser. Square electrical pulses are applied to the laser through its RF input. The signal generator is used to trigger both the pulse generator and the synchroscan unit.

The fiber output of the laser is connected directly to the optical input of the streak camera. In view of the high sensitivity of the streak camera, care must be taken to ensure that the streak tube is not damaged as a result of an overly high input power. A fiber optic attenuator is used for this purpose. The experimental set-up used is shown schematically in Figure 4.3.
4.2.3 Time-Resolved Spectra

A double-subtractive monochromator whose inner structure is depicted in Figure 4.4 is used in order to compensate for time-dispersion effects present in a single-grating monochromator. Two beams at the same wavelength but with different paths are represented using a dotted and a continuous line. When a single monochromator is used, as for example monochromator A, the dotted line has a longer path than the continuous line. The dotted and straight beams will hit the streak camera photodetector at different moments and will temporal spread in the measurements. The dispersion of a single monochromator is usually of the order of 70 ps (this is a function of grating, numerical aperture, etc. – not a simple thing. Simply be prepared to elaborate further if asked – text is fine). A double monochromator consists of two monochromators placed in series. It provides higher dynamic range but also higher insertion loss due to additional series optic
components. A double monochromator provides equal optical paths to all wavelengths as a result of its mirror symmetry. In the figure, colours following the dotted and continuous lines leave the double monochromator and hit streak photodetector in the same moment.

![Double Monochromator Configuration](image)

**Figure 4.4 Double Monochromator Configuration.**

In order to combine time-resolving and wavelength-resolving capabilities, the experimental set-up depicted in Figure 4.3 is augmented using the SpectraPro-750 double-subtractive monochromator from Acton. The streak camera is mounted on a 1D translation stage designed to support its large mass (25 kg) and to allow fine horizontal alignment with monochromator. Due to the different height of the streak camera and monochromator, a table has been designed and attached to translation stage. For finer vertical adjustment of the two instruments, shims of 1-2 mm have been added between the streak camera and the table. The 6 mm height of the streak photocathode permits a
large tolerance for vertical alignment. The experimental set-up is shown in Figures 4.5 a and b. The schematic of the experimental set-up is presented in Figure 4.6.

Figure 4.5.a Right side view of the TRS experimental set-up: double monochromator, lens, and optical fiber head of the laser.
Figure 4.5.b Left side view of the TRS experimental Set-up: CCD camera, streak camera on translation stage, and double monochromator.

Figure 4.6 Experimental set-up for TRS measurements.
4.3 Conclusions

In the present chapter, the experimental apparatus and methods used to obtain both static and dynamic information on laser behaviour were described. In the following chapter, results obtained using thesis novel experimental apparatus are reported.
Chapter 5

Results

Results of static and dynamic measurements on MQW DFB RW lasers are presented in this chapter. The main static parameters are measured in Section 5.1. This information is necessary in Section 5.2. to define dynamic parameters for direct modulation of the laser used.

5.1 Static Measurements

5.1.1 Introduction

Even if the final aim of the thesis is the dynamic characteristics, static characteristics are needed to define the parameters for direct modulation. For example, if the laser is to be biased just above threshold, and the amplitude of modulation is to be equal to twice the threshold current, then the steady-state light-intensity (L-I) characteristic must be known.

Knowledge of the spectrum of light emission from the laser in the steady state is also required prior to studying dynamic behaviour. This will help in measuring the dynamic chirp during modulation.
5.1.2. Light-Current Characteristics

One of the basic measurements of the laser is the variation of optical power produced as function of the injected current. Threshold current $I_{th}$ and differential efficiency $\eta_d$ are key parameters used to characterise static power characteristics.

The measured light-current characteristic of the laser described in Chapter 3 is shown in Figure 5.1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5_1.png}
\caption{Light-current characteristics.}
\end{figure}

A front-facet differential efficiency of:

$$\eta_d = 0.053 \text{ W/A } \pm 4\%$$

and a threshold current of:

$$I_{th} = 18 \text{ mA}$$

were determined from Fig 5.1.
Differential efficiency expressed in percent is:

\[ \eta_d(\%) = \frac{h\nu\eta}{q} = 1.24/\lambda\eta = 18 \% \]

The low measured efficiency is a consequence of significant fiber coupling loss.

5.1.3 Voltage-Current Characteristics

The measured DC voltage bias as a function of current applied is shown in Figure 5.2. The differential resistance of the packaged laser is close to 50 Ω. The differential resistance of the laser itself is known to be less than 10 Ω.

![Figure 5.2 Voltage-current characteristic.](image-url)
5.1.4 Spectrum

The steady-state spectrum of a 1310 nm DFB laser was obtained using an optical spectrum analyser as described in Chapter 4.1. As shown in Fig. 5.3.a, most of the power is concentrated in a single longitudinal mode in the long wavelength side of the DFB grating stopband.

![Spectrum of DFB laser on a large wavelength range using OSA.](image)

The spectral distance between Fabry-Perot longitudinal modes measured in Figure 5.3.b is \( \Delta \lambda = 0.85 \) nm and the width of the DFB stopband is \( \Delta \lambda_{\text{Bragg}} = 3 \) nm.

The wavelength spacing of adjacent Fabry-Perrot longitudinal modes is given by:

\[
\Delta \lambda = \lambda^2 / 2 \mu \omega L;
\]
Figure 5.3.b Stopband and main mode spectrum of 1310 nm DFB laser using OSA with higher resolution and shorter wavelength span.

Assuming a refractive index for InGaAsP of $n = 4$, the cavity length is estimated to be $L = 250 \, \mu m$ which is consistent with physical specifications for the laser under test.
5.2 Dynamic Behaviour Measurements

In the present section, measurements of time-averaged spectra, time-resolved spectra, and temporal variation of the total intensity are reported.

5.2.1 Time Averaged Spectra under Sinusoidal Modulation

Averaged spectral characteristics were acquired for sinusoidal direct modulation at various frequencies, amplitudes and bias conditions. Frequencies between 0.1 MHz and 990 MHz, modulation voltage between 2 and 3 Volts, and DC bias between 0 and 1.5 $I_{th}$ were used.

In a fibre-optic communication system, spectral broadening of optical signals causes spreading of pulses in time as a result of chromatic dispersion in the fibre. Conventionally, spectral broadening is measured to a level of about −20 dB.

For sinusoidal modulation between 0 mA and 60 mA, there is a broadening of the spectral bandwidth of $BW_{-20dB} = 0.5$ nm as seen in Figure 5.4. The graph also illustrates that above about 200 MHz sinusoidal modulation frequency the laser no longer followed the modulation current. It is for this reason that semiconductor lasers must be biased slightly above threshold for a fast response to be obtained. For a modulation current from 0 to 60 mA, there is a broadening of the spectral bandwidth of $BW_{-20dB} = 0.5$ nm. There is a 0.04 nm increase in the spectral linewidth at 990 MHz direct modulation frequency compared to the linewidth at 10 MHz modulation frequency. This linewidth broadening due to direct modulation is interpreted as average chirp.
Figure 5.4. $I_0 = 0\text{mA}, I_1 = 60\text{mA}$.

The time averaged spectra showed in Figure 5.5 is obtained when the laser is biased above threshold, modulated from 25 mA to 85 mA. The increase in the time averaged spectral linewidth with the modulation is much smaller than in Figure 5.4, proving that modulation above threshold will reduce the chirp.
5.2.2. Temporal Behaviour under Square Pulse Modulation

With the experimental set-up shown in Figure 4.3, the temporal behaviour of the laser under square pulsed modulation was characterised and is reported in this section.

A typical streak camera image obtained with this set-up is shown in Figure 5.6. The variation of the total optical intensity in a temporal range of 1700 ps can be seen in the figure. The horizontal axis represents time and the vertical the optical intensity. The camera image is seen at the bottom of the figure. Laser relaxation oscillations measured by reading the time duration between subsequent peaks, of period ~ 140 ps can also be observed.
In order to distinguish between electrical oscillations and laser relaxation oscillations, it is important to have knowledge of the temporal voltage profile applied during direct modulation of the laser. Figures 5.7 and 5.8 show the voltage pulses applied for amplitude modulation of 2 V and 3 V for different bias voltages. Electrical oscillations with a period of 500 ps were observed. The rise time is approximately 200 ps (the interval between 10% to 90%). The fall time is approximately 250 ps. The pulse width is around 3.7 ns, the minimum achievable using this pulse generator. The period of the pulses is 10 ns in order to correspond with the synchroscan frequency of the streak camera.
Figure 5.7 Voltage pulse for a modulation excursion of 3 V at different d.c. biases.

Figure 5.8 Voltage pulse for a modulation excursion of 2 V at different d.c. biases.
The optical response of the laser output to these voltage modulation conditions is shown in Figures 5.9 and 5.10. When the laser is biased near threshold or at 0 V bias, the optical intensity increases very sharply, but relaxation oscillations are very pronounced and the time necessary to reach a steady state is long. The settling time is longer than 500 ps for 0 V bias and 3 V peak. As the bias is increased above threshold, damping becomes stronger and the amplitude of the relaxation oscillations decreases until these eventually disappear when the laser is biased at 1.5 V and 2 V. At bias higher than 1.5 V, the rise time is slower and the light output follows the shape of the electrical pulse.

At 0 V bias voltage and a modulation excursion of 3 V, the frequency of the relaxation oscillations is 7.2 GHz. This corresponds, conform Equation (2.25), to a modulation bandwidth of 11.2 GHz. For 1 V bias voltage and the same modulation excursion of 3 V, relaxation oscillation increases to 11.6 GHz with an estimated bandwidth of 18 GHz. At 1.2 V bias voltage the relaxation oscillation start to decrease at 11.1 GHz and disappears for 1.5 V and 2 V bias voltage due to the overdamping effect. When a smaller modulation excursion of 2 V is applied, as it is shown in Figure 5.11, oscillations of 5 GHz were observed whereas for higher bias of 1.2 V, the relaxation oscillation frequency is increased to 10 GHz.
Figure 5.9 Temporal behaviour for a 3 V modulation excursion at different bias current.

Figure 5.10 Temporal behaviour for 2 V modulation excursion and different bias current.
The feature which appears near 890 ps in Fig. 5.9 results from overexposure of the photocathode in that region during focusing mode.

5.2.3. Time Resolved Spectra under Square Pulse Modulation

Time-resolved spectra of the laser studied were obtained under square pulse modulation. The experimental set-up used for these measurements has been shown in Figure 4.3 of Chapter 4. The electrical pulses were applied with the same settings as in Figures 5.7 and 5.8.

Time resolved spectra for current modulation from 2 V to 5 V are shown in Figure 5.11.a. The intensity is represented in colour as a function of wavelength and time. Initially, when the current is low, the optical pulse spectrum peaks at the wavelength 1309.82 nm. As the current is increased, the spectral peak shifts toward a lower wavelength around 1309.74 nm.
Figure 5.11.a Contour plot for TRS rising edge at 2V bias voltage and 3V modulation excursion.

For a better visualisation, a three dimensional plot of the same measurement is shown in Figure 5.11.b.

Figure 5.11.b 3D plot of TRS rising edge for 2V bias and 3V modulation excursion.
The falling edge of the light pulse is shown in Fig. 5.12.a and 5.12.b. Figure 5.13.a allows the value of the chirp to be measured easy. As expected, since there is no ringing on the falling edge of the electrical pulse, none is found in the light output.

**Figure 5.12.a** Contour plot for TRS falling edge at 2V bias voltage and 3V modulation excursion.

**Figure 5.12.b** 3D plot for TRS falling edge at 2V bias voltage and 3V modulation excursion.
A red shift of 0.08 nm from the lasing wavelength was observed during turn-off as revealed in Fig. 5.12.

The time-resolved spectrum is shown in Figure 5.13a and b for a laser modulated at 1.2 V bias and 3 V modulation excursion. The chirp cannot be detected, the light at the low bias being lower than the sensitivity of the system.

The time-resolved spectrum for a laser biased at 0 V with a peak-to-peak modulation of 3 V is shown in Figure 5.14. There is a larger broadening of the spectrum than when the laser is biased above threshold.

Figure 5.13a Contour plot for TRS rising edge at 1.2 V bias and 3 V modulation excursion.
Figure 5.13.b 3D plot for TRS rising edge at 1.2 V bias and 3 V modulation excursion.

Figure 5.14 Contour plot for TRS rising edge at 0 V bias and 3 V modulation excursion.
5.3 Discussion

5.3.1 Static Measurements

Slope efficiencies for the gain coupled DFB laser are typically 0.1-0.2 mW/mA measured at each facet. This refers to a Chip on Carrier (COC) measurement in which nearly all of the light emitted from one facet of the laser is coupled using free-space optics into the detector. In the present work, the laser is fiber-coupled using a ball lens into a single-mode fibre with coupling efficiency in the range 30%-40%.

A shift was observed in the lasing wavelength towards longer wavelengths at higher DC current biases. This can be explained by the heating of the laser, which causes shrinkage in bandgap of the active region material. Thermal effects on this timescale are addressed using a thermoelectric cooler.

5.3.2 Dynamic Measurements

Time averaged spectra under sinusoidal modulation at frequencies up to 990 MHz and different bias voltages reported in Section 5.2.1, has shown a higher temporal averaged chirp in the case where the bias corresponding to “0” bit is below threshold than above.

Temporal behaviour under square pulse modulation was reported in Section 5.2.2. In Chapter 2 it was predicted that the frequency of the relaxation oscillations should increase with the bias voltage for low values of bias. As it can be seen in Figure 5.10 the relaxation oscillation increases from 7.4 GHz at 0 V voltage corresponding to “0” bit to 11.62 GHz at 1 V. For further increase in the bias the nonlinear effects start to dominate and due to the overdamping effect the oscillation in optical power decreases and eventually disappears for 1.5 and 2 V bias voltage as it can be seen in Figure 5.9 and
5.10. The results are in good agreement with simulations presented in Figure 2.4 from Chapter 2. It can be noticed in Figure 5.9 that the delay time between current step and optical response is reduced with the DC bias. For Figure 5.10 the delay has been changed between measurements on purpose to be able to see on the streak camera screen all the oscillations in the optical power when the laser is biased at 0 V.

Higher modulation bandwidth implies higher relaxation oscillation frequency, which is achievable by increasing the optical output power of the laser by higher bias voltages. A further effect is the increase in damping factor as the bias voltage is increased as revealed in the relation between damping factor and relaxation oscillation [9]. Disappearance of the relaxation oscillations for 1.5 V and 2 V bias implies that region of critical damping has passed and overdamped regime has been reached as proved also in simulation and mentioned by Corzine [9]. The response of the laser is slower in this case as evidenced by increased rising and falling times seen in Figures 5.9 and 5.10 of Section 5.2.2. In practical application, the laser is overdamped to avoid high oscillation in the optical power that can cause errors in the transmission of information. A larger and cleaner eye is obtained using this approach.

A strong damping factor has been observed in gain-coupled DFB laser studied. The disappearance of the relaxation oscillation is caused by gain saturation, which cause the overdamped of the relaxation oscillation.

In time-resolved spectral measurements reported in Section 5.2.3, a chirp of 0.08 nm was measured, as seen in Fig. 5.11.a, during direct modulation between 2 V and 5 V. Over the measured interval, the lasing wavelength oscillated between 1309.74 nm and 1309.76 nm. This is a consequence of the ringing of the driving pulse.
A similar value of the chirp was measured when the falling edge of the pulse was studied.

In agreement with theory, a higher chirp of 0.1 nm was measured when the laser was modulated between 1.5 V and 4.5 V.

The value of chirp obtained from TRS measurements shown in Figure 5.14 cannot be measured when the bias current corresponding to the lower intensity is 0 V and 1.2 V. Below and very near the lasing threshold, the optical intensity of the laser is lower than that which can be detected by the system.

5.4 Conclusions

In the present chapter, results were reported for the first time for measurement, using streak camera in combination with a double-subtractive monochromator, of the time-resolved spectral behaviour of 1.3 μm DFB lasers designed for 10 Gbps modulation.
Chapter 6

Conclusions

6.1 Summary of Work

This work represents the first experimental report of time-resolved measurement of directly-modulated telecommunications-wavelength lasers at 1310 nm using a double subtractive monochromator combined with streak camera. Measurement of the spectro-temporal evolution of laser emissions under these conditions is of critical importance in enabling metropolitan-area and regional networks based on cost-effective source technologies.

It was found that combination of streak camera and double-subtractive monochromator could provide sub-2 ps temporal resolution and sub-0.046 nm wavelength resolution with adequate sensitivity at telecommunications wavelengths. It was demonstrated that it is possible to observe the detailed profile of transient chirping over excursions of 0.08 nm and 0.1 nm in directly modulated lasers using this newly assembled apparatus. Previous results of time resolved spectrum systems exhibited lower temporal resolution in the vicinity of 70 ps. The experiment reported herein proved that it is possible to build a system for detailed analysis of picosecond phenomena such as those arising due to spectral and spatial hole burning, carrier transport effects, and the influence of hot carriers.
6.2 Future Research

Use of higher-speed electronics, instead of the available pulse generator which provided rise/fall times of 180 ps, would allow probing into the range of 10 Gbps and even 40 Gbps optoelectronic sources of interest in future generations of optical networks.

Introduction in the system of a frequency converter would allow compatibility of a laser pulsed at multiples/submultiples of 10 GHz with the synchroscan frequency of the streak camera of 100 MHz. This would permit study of the transient effects during laser modulation at high frequency allowing that the synchroscan frequency limitation to not be a problem.

Enhanced control over pulse width would provide a basis for studying the dependence of chirp on the details of bit patterning, permitting evaluation of thermal chirp associated with a long stream of “1” bits.
References:


