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Pulse-shaping to reduce the chirping effects of DFB laser diodes and pulse broadening

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The University of Arizona, 1992
PULSE-SHAPING TO REDUCE THE CHIRPING EFFECTS OF DFB LASER DIODES AND PULSE BROADENING

by

Zhiqiang Yang

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1992
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APPROVAL BY THESIS DIRECTOR

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Date
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ABSTRACT

In this thesis, a computer simulation has been done to evaluate the wavelength chirping and pulse broadening effects induced by the direct intensity modulation using Distributed Feedback (DFB) laser diodes. In the simulation, a DFB laser diode is driven by either square wave current pulses or pulses with a small current Step in the Leading Edge (SLE). A comparative study is performed to justify the effectiveness of using SLE waves in modulation to reduce wavelength chirping and pulse broadening.

Numerical results from the single-mode rate equations show that the SLE wave modulation reduces the wavelength chirping and pulse broadening by a factor of 2. The optimal SLE pulse has a prepulse duration of 0.15 ns and a prepulse current level of 70.0 mA.
CHAPTER 1

Introduction

1.1 Overview

Information transmission through optical means dates back to ancient times. However, the breakthrough of optical transmission did not occur until a quarter century ago when Kao and Hockham [1] used a cladded glass fiber as the transmission medium for sending light signals. Soon later, low-loss fibers were made possible [2], and semiconductor lasers were successfully developed as the light source [3]. The optical fiber communications then emerged from its infancy into the limelight. Today, terrestrial and undersea lightwave systems are being actively deployed in North America, Europe, and Japan.

As illustrated in Figure 1.1(a)[4], a basic optical fiber transmission link consists of a transmitter, an optical fiber, and a receiver. The transmitter has a light source such as a laser diode (LD) which is modulated by a sequence of input bits in digital communications. Specifically, the light source is turned on and a light pulse is generated if the input is “1”, and no light pulse is generated if the input is “0”. Therefore, this modulation is often called “on-off” keying (OOK). The light pulses generated are
Figure 1.1: (a) A basic digital lightwave transmission link; (b) A cascaded lightwave transmission system of repeated basic links.

One important objective of most lightwave transmission systems is to transmit signals faster and over longer distances. They are characterized by their bandwidth-distance product [5]. To increase the transmission distance, we need to first reduce
the fiber attenuation. This motivates one to shift the operational wavelength from 0.85 \( \mu m \) to 1.3 \( \mu m \) and even further to 1.55 \( \mu m \) [4]. Studies [8] have shown that the attenuation coefficient is 1 \( dB/Km \) at 0.85 \( \mu m \), 0.4 \( dB/Km \) at 1.3 \( \mu m \) and 0.2 \( dB/Km \) at 1.55 \( \mu m \) in a typical fused silica fiber. In addition to attenuation, dispersion is another that limits bandwidth-distance product [5].

Dispersion results in a pulse becoming broader as it travels along a dispersive fiber [5]. This pulse broadening blurs out the distinctions between adjacent pulses. Therefore, adjacent pulses must be separated by a minimum distance. The minimum required separation between pulses is larger when the transmission distance is longer. Figure 1.2 illustrates this point schematically. In Figure 1.2(a) a lower transmission rate is used so that after transmission through a long distance the adjacent pulses are still distinguishable; Figure 1.2(b) shows that at a higher transmission rate the adjacent pulses overlap each other for the same transmission distance.

Although fiber attenuation is minimized at 1.55 \( \mu m \) [4], there is a non-zero fiber dispersion. Fiber dispersion is, in general, proportional to the linewidth of the light signal [8]. To reduce the dispersion effect, the linewidth of a light source should be as small as possible. Therefore, a narrow linewidth light source, such as a Distributed Feedback (DFB) laser diode, is often used to reduce the dispersion effect. However, when a DFB laser diode is modulated directly by the driving current its linewidth is broadened. This linewidth broadening (or chirping effect) combined with fiber dispersion can cause significant pulse broadening [8]. Since the pulse broadening
Figure 1.2: Illustration of pulse broadening effect on transmission rate (a) Lower transmission rate system; (b) Higher transmission rate system.
effect is more significant at a higher transmission rate and longer distance, it can ultimately limit the achievable system performance. There are many modulation techniques such as external modulation [9] and frequency-shift-keying (FSK) [10] that are used to reduce the chirping effect. Some of them are very sophisticated. However, because these sophisticated methods are costly and technically complicated, direct intensity modulation would be more attractive if some simple modification of the existing modulation techniques could be found that reduced the wavelength chirping.

1.2 Objective of Thesis

To reduce wavelength chirping researchers have made significant efforts to develop new laser structures [11] and sophisticated modulation techniques [9][10]. In this thesis we will take a different approach. We will study the pulse-shaping approach [29][30]. Because of its simplicity, this approach is very practical and requires no significant hardware modification of conventional optical fiber communication systems. This thesis is intended to investigate in depth how wavelength chirping and chromatic dispersion can be reduced by shaping the driving current waveforms.

1.3 Outline of Thesis

In the rest of the thesis, Chapter 2 first gives a general discussion on the basics of chromatic fiber dispersion. The concept of group velocity and group delay are explained because they succinctly describe the chromatic dispersion effect [4][5].
Chapter 3 describes the optical feedback mechanisms in a DFB laser diode. To establish a theoretical basis for a later numerical study of chirping effects, this chapter also discusses the single-mode rate equations and wavelength chirping mechanisms.

Chapter 4 solves the rate equations numerically using two different driving current waveforms: a square pulse and a pulse with a small current Step in the Leading Edge (SLE). Transient carrier densities; photon densities; and the wavelength chirping and power spectrum, are calculated and compared to study the effectiveness of pulse-shaping in reducing the wavelength chirping.

The ultimate goal of this thesis research is to increase the fiber transmission system performance by pulse-shaping. Wavelength chirping does not degrade the system performance by itself. It is the combining effect of chirping and fiber chromatic dispersion that causes the degradation [8]. To demonstrate the effectiveness of pulse-shaping in improving the system performance, Chapter 5 investigates the chirping effect in an overall transmission system. Chapter 6 summarizes this thesis research and indicates possible future directions.
CHAPTER 2

Chromatic Dispersion of the Single-Mode Optical Fiber

2.1 Introduction

As discussed in the first chapter, chromatic dispersion and fiber attenuation are two limiting factors for faster and longer optical fiber transmission systems. Using light sources at a wavelength of 1.55 μm, one can minimize the fiber attenuation [4][12]. However, at a wavelength of 1.55 μm, the dispersion in the fiber is non-zero [12]. This non-zero dispersion broadens the propagating pulses in a fiber [8]. This chapter will discuss the basic characteristics of pulse propagation in a dispersive fiber in an effort to understand better this pulse broadening effect.

2.2 Group Velocity and Group Delay

The shape of an optical pulse becomes broader as it propagates along a single-mode fiber [8]. This pulse broadening is called dispersion [8]. In single-mode fibers, dispersion is due to different propagation velocities at different wavelengths. There are two mechanisms which contribute to this dispersion: chromatic (material) dispersion and waveguide dispersion [5]. Chromatic dispersion is due to the fact that the
Figure 2.1: Single-mode-fiber total dispersion versus waveguide and material dispersion (reproduced from Ref.[28]).

refractive index of the fiber material is a function of the wavelength [5], and waveguide dispersion occurs because the wave number along the direction of propagation is also wavelength dependent [5]. In general, chromatic dispersion is more significant than the waveguide dispersion [5]. Experimental results [12] shown in Figure 2.1 indicate that chromatic dispersion can be used to approximate the total dispersion in a single-mode fiber. Therefore, we will focus our attention on chromatic dispersion in this thesis.

To understand the source of dispersion, we need to know how the propagation velocity of a pulse in the fiber is dependent on wavelength. There are two different
velocities defined for an electromagnetic wave [13]. The first one is called phase velocity ($v_p$). The meaning of the phase velocity is the velocity of a constant phase plane of a wave that moves in a medium. Figure 2.2 gives a clear illustration of the phase velocity, where the electric field $E$ of light varies sinusoidally with time ($t$) and distance ($z$). At time $t = 0$ and $z = 0$, i.e. at point A, the amplitude of the $E$ field is zero. When time $t = t_1$ the point A has moved a distance of $z_1$ and the amplitude is still zero. If the angular frequency $\omega$ and the propagation constant [13]

$$\beta = \frac{2\pi}{\lambda} \quad (2.1)$$

are introduced, then

$$\sin(\omega t_1 - \beta z_1) = 0 \quad (2.2)$$

is the equation for the constant phase plane with phase equal to zero.

This gives infinity of solutions

$$\omega t_1 = \beta z_1 + m\pi, \quad m = 0, \pm 1, \pm 2, \ldots \quad (2.3)$$

In less than one period movement cannot include the $m\pi$ term. So, we have

$$\omega t_1 = \beta z_1. \quad (2.4)$$

The phase velocity is then defined as

$$v_p = \frac{z_1}{t_1} = \frac{\omega}{\beta} \quad (2.5)$$
The wavelength $\lambda$ in a fiber with refractive index $n$ is related to the wavelength $\lambda_f$ of the same frequency light in free space through

$$\lambda = \frac{\lambda_f}{n}$$

Hence [13], the wave number

$$\beta = \frac{2\pi}{\lambda} = \frac{2\pi n}{\lambda_f} = \frac{wn}{c}$$

and the phase velocity in the fiber [8] follows immediately:

$$v_p = \frac{c}{n}$$  \hspace{1cm} (2.6)
It is interesting to note that if \( n \) varies with frequency, then \( v_p \) will also vary. The concept of phase velocity is only useful to monochromatic light. In reality, it is impossible to have pure monochromatic light [8]. Even for single-mode DFB laser diodes the linewidth is non-zero [25]. Therefore, a more useful concept, called group velocity (\( v_g \)), which represents the velocity of a wave packet, has been introduced. A wave packet is a light pulse that consists of many frequency components. Therefore, group velocity is more appropriate to describe the speed of pulse propagation and is thus an important observable quantity. Note here the group velocity is only define for packet having a narrow linewidth. In our study the light source is a single-mode DFB laser diode, which has a very narrow linewidth. Therefore using of group velocity in the following analysis is appropriate.

The group velocity in a medium with refractive index \( n \) is defined as [13]:

\[
  v_g = \frac{d\omega}{d\beta}
\]

Using

\[
  \beta = \frac{n\omega}{c}
\]

we have

\[
  \frac{d\beta}{d\omega} = \frac{1}{c}(\omega \frac{dn}{d\omega} + n)
\]

Since

\[
  \omega = \frac{2\pi c}{\lambda_f}
\]
where $\lambda_f$ is the free space wavelength, we have

$$\frac{dn}{d\omega} = -\frac{\lambda_f^2}{2\pi c} \frac{dn}{d\lambda_f} \quad (2.9)$$

Substituting equation 2.9 into equation 2.8, we obtain

$$\frac{d\beta}{d\omega} = \frac{1}{c} (-\lambda_f \frac{dn}{d\lambda_f} + n)$$

Therefore,

$$v_g = \frac{d\omega}{d\beta} = (\frac{d\beta}{d\omega})^{-1} = \frac{c}{n - \lambda_f \frac{dn}{d\lambda_f}} \quad (2.10)$$

If we define

$$n_g = n - \lambda_f \frac{dn}{d\lambda_f}$$

as the group refractive index, equation 2.10 reduces to

$$v_g = \frac{c}{n_g} \quad (2.11)$$

One can then define the group delay $\tau_g$ over the propagation distance $L$ in terms of the group velocity (equation 2.11) as

$$\tau_g = \frac{L}{v_g} = \frac{n - \lambda_f \frac{dn}{d\lambda_f}}{c} L$$

$$= \left(\frac{n - \lambda_f \frac{dn}{d\lambda_f}}{c}\right) L$$

$$= \frac{n_g L}{c}$$

$$= \frac{n_s L}{c} \quad (2.12)$$
2.3 Chromatic Dispersion and Dispersion Limits

From the discussion in the previous section, we see that the group delay is a function of wavelength. If we expand the group delay in terms of a Taylor series with respect to a center wavelength $\lambda_0$ and ignore the higher order derivatives, we have

$$\tau_g(\lambda_f) \approx \tau_g(\lambda_0) + \frac{d\tau_g}{d\lambda_f}(\lambda_f - \lambda_0)$$

Therefore, if a light source has a linewidth $\Delta \lambda$ ($\Delta \lambda = \lambda_f - \lambda_0$), the delay variation $\Delta \tau_g$ is

$$\Delta \tau_g = \frac{d\tau_g}{d\lambda_f} \Delta \lambda$$
where

\[ \frac{1}{L} \frac{d\tau_g}{d\lambda_f} = -\frac{\lambda_f}{c} \frac{d^2 n}{d\lambda_f^2} \]

(2.13)

\[ = -D(\lambda_f). \]

The term \( D(\lambda_f) \) is called chromatic (material) dispersion of the optical fiber; its units are normally \( ps/(nm \cdot Km) \). The negative sign indicates that a shorter wavelength component travels faster than a longer wavelength component. The chromatic dispersion varies with different glass fibers. Figure 2.3 shows the variation of chromatical dispersion with the wavelength for a typical fused silica glass fiber. Notice that the chromatic dispersion is close to zero at the vicinity of 1.3 \( \mu m \) and it is not zero at the vicinity of 1.5 \( \mu m \).

Thus far, we have derived the chromatic dispersion for a single-mode fiber. We know that dispersion limits the transmission distance and the transmission rate. Now we are going to derive this limit.

Suppose we have a stream of “1”s and “0”s as shown in Figure 2.4, where a “1” corresponds to a light pulse of width \( T_0 \). The bit rate \( B \) in this case is simply \( 1/T_0 \). Because of the fiber dispersion, the pulse is broadened to \( T_r \) at the receiver side. This pulse broadening effect causes the adjacent pulses to overlap (Figure 2.4(a)). In addition, this effect also affects the “0” (corresponding to non-pulse) in between two pulses (as shown in Figure 2.4(b)). Therefore, the bit error rate (BER) increases. If we neglect the noise effect to correctly detect the “0” in between two pulses, we
require that

\[ T_r - T_0 \equiv \Delta T \leq T_0 \]

or

\[ \Delta T \leq \frac{1}{B}. \]

In reality, the noise plays a large role in determining the maximal transmission distance. Therefore, we require that [45]

\[ T_r - T_0 \equiv \Delta T \leq \frac{T_0}{2} \]

or

\[ \Delta T \leq \frac{1}{2B}. \]

As shown in Figure 2.1 the total dispersion of single-mode fiber can be approximated by chromatic dispersion. Therefore we have

\[ \Delta T \approx D(\lambda_f) \cdot \Delta \lambda \cdot L \]

Combing last two equations gives us

\[ L \cdot B \leq \frac{1}{2 \cdot D \cdot \Delta \lambda} \]

This equation sets an upper bound of the bandwidth-distance for an optical fiber communication system. From the equation we can see that there are two means to increase this limit. We can either decrease the dispersion \( D \) or reduce the linewidth of the light source. An example of the first approach is using a dispersion-shift fiber, which shifts the minimum dispersion point of a fused silica fiber from near 1.3\( \mu m \) to
Figure 2.4: Illustration of inter-pulse interference.
the vicinity of 1.55 $\mu m$ [4]. The second approach is to reduce the linewidth $\Delta \lambda$ [5] and is the focus of this thesis. As mentioned in Chapter one, direct intensity modulation of DFB laser diodes broadens the linewidth. This is discussed in Chapter 3. In Chapter 4 and Chapter 5 we will discuss how to reduce the linewidth by shaping the driving current waveform.
CHAPTER 3

Characteristics of the DFB Laser Diode

3.1 Introduction

We have already mentioned previously that even for single-mode Distributed Feedback (DFB) laser diodes the spectral linewidth is considerably broadened under direct modulation. This phenomena is related to the intrinsic characteristics of the laser diodes. To study the spectral broadening, a model is needed to describe the dynamics of some operational properties of DFB laser diodes. The model is based upon rate equations because they characterize the rate of change in both the photon density and the carrier density inside the laser active layer.

A rigorous derivation of the rate equations for laser diodes has to be based on quantum theory [27]. Because of the extreme complexity, it has rarely been used. Instead, the classical Maxwell field equations and a phenomenological approach are commonly used. In this thesis, we will employ the phenomenological approach.

Although the phenomenological model does not include any structural parameters of the DFB laser diodes, an introduction to their structure will help us to understand and appreciate their unique feedback behavior. In this chapter we first introduce
the basic structure of a DFB laser diode and discuss how the structure affects the wave behavior in the cavity. Then, we describe the phenomenological approach and explain the rate equations in detail. Finally, a qualitative discussion of the wavelength chirping mechanisms is introduced to establish a theoretical base for the numerical study of wavelength chirping discussed in Chapter 4 and Chapter 5.

3.2 The Unique Structure of the DFB Laser Diode

The Bragg reflection structure of a DFB laser diode causes the optical waves inside the cavity to behave differently from the conventional Febry-Perot-type (F-P) laser diodes. As a result, DFB laser diodes generate only one longitudinal mode. To understand how the Bragg reflection structure selects the single longitudinal mode inside a laser cavity this section first describes the unique structure of a DFB laser diode and then explains how the structure affects the wave propagation inside the cavity.

Unlike the Febry-Perot-type laser diode, the DFB laser structure [21] has an additional optical feedback mechanism for laser operation. The necessary optical feedback comes from a corrugated grating fabricated on the active waveguide of the DFB laser diode. Such a feedback structure can be realized in a semiconductor by etching a periodic structure along the longitudinal axis of the diode and then growing a different material layer on top of the etched structure. As a wave travels in
this corrugated optical waveguide, it is reflected back on its path via Bragg reflection. This optical feedback is distributed throughout the active region. There are a number of variations of the periodical corrugation structures, such as phase-shift and phase-adjust corrugation structures [25]. This study is only concerned with the basic structure shown in Figure 3.1. In this structure the waveguide varies periodically with a period of $\Lambda$.

The reason for distributing the optical feedback mechanism throughout the active region can be understood as follows [26]. Considering the system illustrated in Figure 3.2, we assume that a strong electric field with an amplitude $E_0$ propagates to the right ($E^+$) in the corrugated optical waveguide with negligible influence from the corrugation except at its edges. A small portion of the electric field is reflected

Figure 3.1: A schematic diagram of a DFB laser diode.
back to the left ($E_i^-$, $i = 1, 2, 3, ...$) at planes A, B, C, ..., N. The reflected individual small wave packets add together with a different phase delays. For instance, at plane A the total field traveling to the left consists of all the small wave packets reflected at planes to the right of plane A, i.e. planes B, C, ..., N. Therefore, the total field traveling to the left at plane A should be

$$E^-(z = \Lambda) = r E_0 + r E_0 t^2 e^{-j2\beta A} + r E_0 t^4 e^{-j4\beta A} + \ldots$$

where the factors $2i\beta A$ ($i = 1, 2, 3, ...$) represent the phase delays, $r$ is the reflection coefficient and $t$ is the transmittance at each corrugation.

If $2\beta A$ is an integer ($m$) number of $2\pi$ radians, i.e.,

$$2\beta A = 2m\pi, \quad (3.1)$$

the individual small reflected fields add in-phase. Substituting

$$\beta = \frac{2\pi n}{\lambda_f}$$
into equation 3.1, one obtains
\[
\frac{4\pi \Lambda n}{\lambda_f} = 2m\pi.
\]
Therefore, the periodic guiding structure provides a wavelength selection mechanism, and the wavelength should satisfy the following condition:

\[
\lambda_f = \frac{2\Lambda n}{m}. \quad (3.2)
\]

More importantly, we can calculate the wavelength space between longitudinal modes using equation (3.2). We note that in equation (3.2) the integer \( m \) is small because

\[
m = \frac{2\Lambda}{\lambda}.
\]

and usually \( m = 1 \) [27]. The wavelength space between the first mode and the second mode is

\[
\Delta \lambda_{DFB} = 2\Lambda n \left[ \frac{1}{1} - \frac{1}{2} \right] = \Lambda n = \frac{\lambda_f}{2}.
\]

If we compare this wavelength space with that for Febry-Perot-type laser diodes having a cavity length \( L \) [5],

\[
\Delta \lambda_{FP} = 2Ln \left[ \frac{1}{m} - \frac{1}{m+1} \right] \approx \frac{2Ln}{m^2} = \frac{\lambda_f^2}{2Ln} = (\frac{\lambda_f}{2})(\frac{\lambda_f}{Ln})
\]

Here the integer \( m \) is assumed large because

\[
m = \frac{2L}{\lambda}.
\]
We can see that the mode separation in DFB laser diodes is far greater than that in F-P laser diodes because by design we have

$$\lambda_f << Ln.$$  

With the basic characteristics of DFB laser diodes understood, the next section explains the dynamics of DFB laser diodes that are important to our chirping study.

### 3.3 Dynamic Characteristics of the DFB Laser Diode

#### 3.3.1 Rate Equations

Laser dynamics are commonly described by a pair of rate equations governing the photon density ($S$) and carrier density ($N$) inside the active layer of laser diodes as [25]:

$$\frac{dN}{dt} = \frac{\eta I_p}{qV} - \frac{N}{\tau_n} - B N^2 - C N^3 - gS \tag{3.3}$$

and

$$\frac{dS}{dt} = \Gamma gS - \frac{S}{\tau_p} + \beta BN^2 \tag{3.4}$$

where

$$g = g_0 \frac{(N - N_0)}{(1 + \epsilon S)} \tag{3.5}$$

is the optical gain from the stimulated emission of photons inside the active layer.

The detailed explanation of the optical gain will be given later. The parameters of equations 3.3, 3.4 and 3.5 are explained in Table 3.1 [25] [27][36][38].
Table 3.1: Typical Values and Explanations of Modeling Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical Value</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>0.8</td>
<td>Current injection efficiency</td>
</tr>
<tr>
<td>$I_p$ [Coulomb/s]</td>
<td>$1.6 \times 10^{-10}$</td>
<td>Pumping current</td>
</tr>
<tr>
<td>$q$ [Coulomb]</td>
<td>$1.6 \times 10^{-10}$</td>
<td>Electron charge</td>
</tr>
<tr>
<td>$V$ [cm$^3$]</td>
<td>$3.6 \times 10^{-11}$</td>
<td>Active layer volume</td>
</tr>
<tr>
<td>$\tau_n$ [second]</td>
<td>$1.0 \times 10^{-9}$</td>
<td>Carrier lifetime</td>
</tr>
<tr>
<td>$\tau_p$ [second]</td>
<td>$2.0 \times 10^{-12}$</td>
<td>Photon lifetime</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$2.0 \times 10^{-5}$</td>
<td>Spontaneous-emission coupling coefficient</td>
</tr>
<tr>
<td>$g_0$ [cm$^2$]</td>
<td>$7.0 \times 10^{-6}$</td>
<td>Gain constant</td>
</tr>
<tr>
<td>$N_0$ [cm$^{-3}$]</td>
<td>$2.0 \times 10^{18}$</td>
<td>Transparent carrier density</td>
</tr>
<tr>
<td>$\epsilon$ [cm$^3$]</td>
<td>$2.0 \times 10^{-17}$</td>
<td>Gain suppression coefficient</td>
</tr>
<tr>
<td>$B$ [cm$^3$/s]</td>
<td>$1.0 \times 10^{-10}$</td>
<td>Bimolecular recombination</td>
</tr>
<tr>
<td>$C$ [cm$^6$/s]</td>
<td>$2.0 \times 10^{-28}$</td>
<td>Auger recombination</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>0.5</td>
<td>Power confinement factor</td>
</tr>
<tr>
<td>$c$ [cm/s]</td>
<td>$2.9979 \times 10^{10}$</td>
<td>Free space light speed, m/sec.</td>
</tr>
<tr>
<td>$n$</td>
<td>4.0</td>
<td>Refractive index</td>
</tr>
<tr>
<td>$\lambda_0$ [\mu m]</td>
<td>1.55</td>
<td>Desired wavelength of laser diodes</td>
</tr>
<tr>
<td>$h$ [Joule \cdot s]</td>
<td>$2.11 \times 10^{-34}$</td>
<td>Planck constant</td>
</tr>
</tbody>
</table>
The two rate equations (3.3 and 3.4) are coupled together through the stimulated emission term $gS$. Stimulated emission is a forced radiative transition. The essential feature of this transition is that a photon in the same oscillation state is generated by existing photons. When stimulated emission occurs, free carriers are consumed through Electron-Hole Recombinations (EHR). Therefore, it takes the negative sign in the rate equation of the carrier density (3.3). However, photons are generated at the same time. Thus, $\Gamma gS$ has a positive sign in the rate equation of the photon density (3.4). Notice that the stimulated emission term in the rate equation of the photon density has an additional coefficient $\Gamma$. The confinement factor $\Gamma$ determines the fraction of generated photons which are confined within the laser active layer.

The stimulated transition may happen in both directions. Photons may either stimulate a new photon by EHR or stimulate a photon absorption by Electron-Hole Generation (EHG). The net rate of stimulated emission is the difference between the downward and upward transition. Therefore, the net stimulated emission or the optical gain is positive only if population inversion has been reached. The population inversion is achieved only when the carrier density reaches the transparency value $N_0$. Therefore, the net optical gain is proportional to $(N - N_0)$. In equation 3.5, $g_0$ is the proportional constant, and the factor $1 + eS$ is used for gain suppression or gain saturation. The consideration of this gain saturation is based on the fact that the population inversion and, hence, the gain is reduced as the optical field in the active layer increases. The consequences of the inclusion of such a term on relaxation
oscillation damping and wavelength chirping have been discussed at length by Koch and Linke [37].

In addition to the stimulated emission, the spontaneous emission \((BN^2 + N/\tau_n)\) also consumes the carrier density. However, only the bimolecular recombination \(BN^2\) is radiative. Only a small fraction of the radiative spontaneous emission enters the lasing mode. Therefore, the factor \(\beta\) is included in the rate equation of the photon density to account for this behavior. Another term \(CN^3\) is called Auger recombination [25]. Since Auger recombination does not generate any photon, it is included only in the rate equation of the carrier density.

The final term in the rate equation of the carrier density is the input term. Because the laser diode is driven by current \(I_p\), we can convert it into an electron density input rate as \(\eta I_p/qV\). Here a constant \(\eta\) is included to specify the efficiency of the current injection into the active layer. Part of the current \((1 - \eta)\) does not go into the active layer.

From the discussion, the rate equations given are simply a bookkeeping of the supply, annihilation, and creation of carriers and photons inside the laser cavity. They describe the laser dynamics in a very basic manner. They are only approximate equations.
3.3.2 Wavelength Chirping

Wavelength chirping is the central issue in this thesis. An understanding of the wavelength chirping mechanism is crucial for us to design methods to reduce and even eliminate it. From the above discussion we know that the wavelength selectivity of DFB laser diodes is dependent on the optical properties of the waveguide feedback structure [27]. Simplified analysis in section 3.2 showed that the wavelength of the lasing mode of a DFB laser diode was related to the corrugation period ($\Lambda$) and the refractive index ($n$) of the active waveguide by

$$\lambda_f = \frac{2\Lambda n}{m}.$$  

Therefore, if any of the waveguide parameters varies during laser operation, wavelength chirping occurs.

In direct intensity modulation of DFB laser diodes, abrupt injection of current may heat the active waveguide medium and change the waveguide parameters. A study [41] has shown that for higher modulation frequencies (above the order of 10 MHz), wavelength modulation induced by carrier density modulation is more important than that induced by temperature modulation. In this study our modulation frequency is 2 GHz. Thus, wavelength variation caused by temperature modulation is neglected here. We, instead, focus on the effect of carrier density modulation on the waveguide properties. Experimental data [43] has shown that a proportional relationship exists between the refractive index variation and the variation of injected carrier density.
Theoretical analysis [42] has demonstrated that two mechanisms contribute to the effect of free carriers on the optical constant of a semiconductor. The first contribution comes from a free-carrier plasma model. This model predicts a negative shift in the refractive index per free carrier per unit volume, \( n_p \), given [42] by

\[
   n_p = -\frac{2\pi q^2}{n_0 m^*_e \omega^2},
\]

where \( \omega \) is the angular frequency, \( n_0 \) is the cw operation refractive index of the waveguide and \( m^*_e \) is the effective mass of the electrons.

Therefore, the total change of refractive index caused by free electrons through their total changing number \( \Delta n_p(\Delta N) \) is

\[
   \Delta n_p = n_p \Delta N.
\]

where \( \Delta N \) is the variation of free electrons.

The other contribution to the modulation of refractive index arises from the injected electron population occupied in the conduction band [44]. These electrons partially block the photogeneration process where light in the spectral region above the band-gap energy is absorbed and excites electrons from the valence band into the conduction band. This alteration of the photon absorption spectrum modifies the refractive index as can be described by the Kramers-Kronig relation [42]:

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

where \( \Delta \alpha(\omega) \) is the variation of absorption caused by the free electrons. The exact solution of this equation is not easy, and a good approximation is given by Miller [44].
In reality the two contributions always go together. Actual measurements and theoretical calculations [43] show that the total variation of the refractive index caused by both mechanisms lies in the range of $-5 \times 10^{-21}$ and $-11 \times 10^{-21}$. In our simulations a value of $-6 \times 10^{-21}$ was used.
CHAPTER 4

Pulse-Shaping to Reduce Chirping Effects of DFB Laser Diodes

4.1 Introduction

From the discussion in the last chapter, we claim that the intracavity oscillation of the carrier density is the major cause of wavelength chirping in DFB laser diodes. Intuitively, if we can find a method to reduce the oscillation of the carrier density in the cavity, we can reduce the wavelength chirping. One way to accomplish this is to shape the driving current waveform. This approach was first proposed by Olshansky and Fye [29]. In their study, current pulses with a small current Step in the Leading Edge (SLE) [29] were used to solve the multimode diode laser rate equations. They predicted that an ideally shaped current pulse would eliminate the relaxation oscillation of carrier density completely. Further experimental study of this approach [30] demonstrated that SLE wave modulation reduced the transient overshoot and spectral linewidth in the laser light output significantly. However, this approach has been overlooked since then. Researchers have devoted much of their effort to
overcoming these chirping effects to other approaches such as using external modulation [9] and frequency-shift-keying [10]. Because of its simplicity and practicality, the pulse-shaping approach deserves more attention. In this chapter we will study the pulse-shaping approach in depth based on the rate equations (3.3 and 3.4) discussed in Chapter 3.

In section 3.2, we discussed wavelength chirping theoretically. This chapter will focus on a numerical study of the chirping effect. The rate equations will be used as a model of DFB laser diodes to simulate their operation. In the rest of this chapter we first review the basic intensity-modulation characteristics of laser diodes including the chirping effect. We will then discuss how pulse-shaping can reduce the chirping effect and spectral linewidth.

4.2 Basic Intensity-Modulation Characteristics

One important advantage of laser diodes is that they can be directly modulated by the input current. This advantage has been studied and used since the early stages of development of the laser diode [34]. Because of its simplicity and low cost, direct intensity modulation has been used in most optical fiber communication systems.

As we know from Chapter 3, the rate equations describe the mutual dependence between the photon density and carrier density within the laser cavity. The solution to the equations depicts the real-time dynamics of the laser operation. Because the rate equations are nonlinear, an analytical solution is not possible. Therefore, a fourth
order Runge-Kutta algorithm [39] is used in this thesis to numerically integrate the coupled first order differential equations:

\[ \frac{dS}{dt} = \Gamma g S - \frac{S}{\tau_p} + \beta BN^2 \]

and

\[ \frac{dN}{dt} = \frac{\eta I_p}{qV} - \frac{N}{\tau_n} - BN^2 - CN^3 - gS \]

where the parameters were explained in Table 3.1.

The first modulation characteristic studied is the turn-on delay. If a laser diode is switched, on the optical emission will be delayed. This property can be seen from the simulation results using a square wave current pulse as the input to the rate equations.

The current pulse \( I_p \) is assumed to be the following square wave form

\[ I_{\text{square}} = \begin{cases} 
I_{\text{bias}}, & t < 0 \\
I_m, & 0 < t < T_0 \\
I_{\text{bias}}, & t > T_0 
\end{cases} \]

where \( I_m \) is the peak modulation current, \( I_{\text{bias}} \) is the bias current and \( T_0 \) is the pulse period. The bias current is a background current level. Normally, the bias current is not set at zero level. Instead, the threshold current level (\( I_{\text{threshold}} \)) of a DFB laser diode is used as a reference to set the bias current level of that laser diode. The value \( I_{\text{threshold}} \) the current level at which the population inversion just occurs. It can be determined from the rate equation of the carrier density (i.e. equation 3.3). In
particular, by setting 
\[ \frac{dN}{dt} = 0 \]
and using the threshold carrier density \( N_0 \) in place of the time-varying carrier density \( N \) in equation 3.3 we obtain the threshold current level
\[ I_{\text{threshold}} = \frac{qV}{\eta} \left( \frac{N_0}{\tau_n} + BN_0^2 + CN_0^3 \right) \] (4.1)

In their calculation the photon density \( S \) was neglected because at the threshold current level the net optical power is very low.

As a numerical example we use the parameter values from Table 3.1 in equation 4.1 to give the threshold current \( I_{\text{threshold}} = 55 \text{ mA} \). We use the pulse period \( T_0 = 500 \text{ ps} \) (i.e. a bit rate of 2 gigabits/s) and a maximum current level \( I_m = 82.5 \text{ mA} \). To compare the effect of the bias current on the delay and wavelength chirping, two different bias current levels are used: \( I_1^{\text{bias}} = 53 \text{ mA} \), which is below the threshold, and \( I_2^{\text{bias}} = 55 \text{ mA} \), which is at the threshold. The two current pulses with different bias current levels are shown in Figure 4.1 and Figure 4.2.

The solution to the rate equations using the two single pulses is shown in Figure 4.3 and Figure 4.4. As expected, the injected current pulse is not instantaneously converted into an optical pulse. The onset of optical power emission is delayed by time \( t_{\text{delay}} \). This delay time yields an upper limit for the attainable modulation frequency because the turn-on delay should be short compared to the pulse duration. The delay time is dependent on the bias current level. For a bias current below threshold (i.e. \( I_{\text{bias}} = 53 \text{ mA} \)), the delay time \( t_1^{\text{delay}} \) is about twice as long as that
Figure 4.1: Square wave current pulse with bias current level at threshold.

Figure 4.2: Square wave current pulse with bias current level below threshold.
Figure 4.3: Optical pulses generated by the square wave modulation.

\((t^{delay}_{2})\) for bias current at threshold (i.e. \(I_{bias} = 55\) mA), that is

\[ t^{2}_{delay} \approx 2 \times t^{1}_{delay}. \]

The other characteristic we can see from Figure 4.3 is the relaxation oscillations in the optical power emission. This ringing phenomenon sets an important limit for the modulation bandwidth of the DFB laser diode because the modulation frequency must be much smaller than the oscillation frequency. Here again a higher bias current yields a better result. This relaxation oscillation results from an interplay between the photon density and the carrier density inside the laser cavity. Figure 4.4 displays the response of the carrier density to the modulation with different bias levels. Similarly, we reduce the relaxation oscillation of the carrier density by using a higher bias current when a DFB laser diode is turned on. From Chapter 3, we know that a
Figure 4.4: Carrier density response to the square wave modulation.

Figure 4.5: Wavelength chirping due to square wave modulation.
variation of the carrier density causes the refractive index to change; hence, it results in a wavelength shift.

The relationship between the refractive index change and the wavelength chirping can be expressed by [36]:

\[ \Delta \lambda = \frac{\lambda_0}{n} \Delta n \]
\[ = \frac{\lambda_0}{n} \rho \Gamma (N(t) - \bar{N}) \]

where \( \Delta n \) is the total change in the refractive index, \( N(t) \) is the carrier density in the active layer, \( \bar{N} \) is the carrier density at cw operation condition, \( \rho \) is the total change in the refractive index per free electron and the remaining parameters are explained in Table 3.1. Therefore, the time-varying wavelength is

\[ \lambda(t) \approx \lambda_0 \left( 1 - \frac{\Gamma \rho}{n} [N(t) - N_0] \right) \]

This is plotted in Figure 4.5. Clearly, the wavelength chirping is reduced by using a higher bias level.

Therefore, higher bias current levels are required for both fast modulation and lower chirping. However, a compromise must be made between fast modulation and higher receiver sensitivity [35]. Note that the receiver sensitivity decreases as the bias level increases for fixed \( I_m \) [31]. Thus, it is unrealistic to use an extremely high bias level. On the other hand, at a lower bias level the chirping becomes a limiting factor for fast and long distance fiber optics communications. In the next section, an alternative approach will be used to overcome this compromise.
Here we should note that in our previous numerical example we focused our attention on the effect of the bias current level on the delay time and the wavelength chirping without considering other effects. In the case of a higher bias current, the difference between the maximum current ($I_m$) and the bias level ($I_{bias}$) is smaller than its value in the lower bias current level case. To make our previous conclusions more convincing, we performed a new set of new simulations. In the simulations we set $\Delta I$ ($\Delta I = I_m - I_{bias}$) to be the same for both the case of a higher bias current level and the case of a lower bias current level. The results show that $\Delta I$ affects neither the time delay nor the wavelength chirping.

4.3 Pulse-Shaping to Reduce Wavelength Chirping

In this section a current pulse with a small current Step in the Leading Edge (SLE) is used to drive a DFB laser diode. The current pulse $I_p$ takes the following form:

$$I_{SLE} = \begin{cases} 
I_{bias}, & t < 0 \\
I_{pre}, & 0 < t < T_{pre} \\
I_m, & T_{pre} < t < T_0 \\
I_{bias}, & t > T_0 
\end{cases}$$

An SLE wave current pulse is plotted in Figure 4.6. To reduce the turn-on delay and not compromise the receiver sensitivity, the bias current level is chosen at the threshold level. The width $T_{pre}$ and level $I_{pre}$ of the prepulse can assume various values.
As a numerical example, we chose the prepulse duration $T_{\text{pre}} = 100\ \text{ps}$, which is 20 percent of the pulse period $T_0$, and set the prepulse current level $I_{\text{pre}}$ at 65 mA and the peak current level $I_m$ at 82.5 mA. The solutions to the rate equations with this SLE input pulse are shown in Figures 4.7 and 4.8. Along with the SLE wave solution, a square wave solution is also plotted in the same figure for comparison.

The results show that the relaxation oscillation of the emitted optical power (see Figure 4.7) has been significantly reduced by using an SLE wave as the input to the laser diode. This implies a higher modulation frequency limit can be achieved with an SLE input pulse. Similarly, the relaxation oscillation of the carrier density is also greatly reduced as shown in Figure 4.8. The reduced transient oscillation of the carrier density reduces the wavelength chirping as shown in Figure 4.9. It is noted
Figure 4.7: SLE wave modulated optical pulse.

Figure 4.8: Carrier density response to SLE wave modulation.
that a blue shift [22] first occurs when the laser diode is turned on, and a red shift [22] follows when the laser diode is turned off. The blue shift is more severe for the case of square wave modulation. The time delay is increased by SLE modulation.

From the analysis in Chapter 2, we know that by reducing the spectral linewidth of optical pulses we can increase the bandwidth-distance product. To demonstrate the effectiveness of pulse-shaping in increasing the bandwidth-distance product, the spectral linewidth of the SLE wave modulation case is calculated and shown in Figure 4.10.

The spectrum is obtained directly from the time-varying optical power (Figure 4.7) and the time-varying wavelength (Figure 4.9). Notice that both Figure 4.7 and Figure 4.9 have the same horizontal axis, i.e., time. So, at each time point we have the values of both the optical power and the wavelength. Therefore, at each wavelength in Figure 4.9 we have the corresponding optical power. Now, we sort this new data set according to the value of wavelength in an ascending order. Finally, we divide the wavelength range into small sections and take the sum of the optical power within each wavelength section as the power corresponding to the middle point of that section.

In comparison with the square wave modulation, the SLE wave modulation reduces the spectral linewidth by a factor of 2. Therefore, we may expect the bandwidth-distance product would double if SLE wave modulation were used.
Figure 4.9: Wavelength chirping due to SLE wave modulation.

Figure 4.10: Power spectrum resulting from SLE modulation.
Figure 4.11: Changes of spectral linewidth according to the size of the prepulses.

In the previous example, we arbitrarily choose some values for the prepulse duration and prepulse current level. Our simulations show that the size of prepulse affects the wavelength chirping. To attain the optimal size of the prepulse, we systematically choose different values for the prepulse duration and current level. We then generate current pulses with different prepulse durations and current levels as shown in the Figure 4.11. These pulses are used as input in solving the rate equations numerically. The responses of the spectral linewidth to different prepulse durations and current levels are summarized in Figure 4.11. The results show that the choice of the prepulse width and height affects the linewidth significantly. The optimal prepulse obtained from our calculations has a width of 0.15 ns and a height of 70 mA.
5.1 Introduction

From Chapter 2, we know that the combination of the chromatic dispersion of optical fibers and the wavelength chirping of the DFB laser diodes results in pulse broadening. The effect of this pulse broadening increases as the transmission distance increases. This pulse broadening or dispersion introduces intersymbol interference and limits the maximum distance between regenerative repeaters. To evaluate the effectiveness of the pulse-shaping technique in improving an overall fiber optics system, we send a sequences of optical pulses generated by square wave and SLE wave modulations through a single-mode fiber over a certain distance $L$ and then observe the pulse broadening and pulse overlapping. To isolate the effectiveness of the pulse-shaping technique, we neglect any noise effects in this study.

The study is based on the simplified digital lightwave system depicted in Figure 1.1. The input data train is given by

$$I(t) = I_{bias} + \sum_{k=0}^{\infty} A_k I_p(t - kT_0)$$
where \( I_{\text{bias}} \) is the bias current and the sequence \( \{A_k\} \) consists of randomly distributed data values of either "1" or "0". The bit rate is given by \( 1/T_0 \). In this study a two gigabits Non-Return-to-Zero (NRZ) modulation frequency is used. The applied current pulse waveforms \( I_p(t) \) can be either a square wave or an SLE wave as described in Chapter 4. If a square wave is used, the input current pulse \( I_p(t) = I_{\text{square}}(t) \). If an SLE wave is applied, the input current pulse \( I_p \) takes the following different forms according to the data pattern:

\[
I_p(t) = \begin{cases} 
I_{\text{square}}(t), & \text{if the previous pulse is "1"} \\
I_{\text{SLE}}(t), & \text{if the previous pulse is "0"}
\end{cases}
\]

because if the previous pulse is "1" the current pulse does not need to shape its leading edge and if the previous pulse is "0" the current pulse need to shape its leading edge. The input waveform with the optimal prepulse obtained in Chapter 4 is used in SLE wave modulation. The solution for both square wave and SLE wave is plotted together for comparison.

For the square wave modulation, the modulated optical signal at the fiber input is

\[
X_{\text{in}}(t) = \sum_{k=0}^{\infty} A_k P_{\text{square}}(t - kT)
\]

where \( P_{\text{square}}(t) \) is the optical pulse function generated by square wave modulation as shown in Figure 4.3.
If the SLE wave modulation is applied, the modulated optical signal at the fiber input is

\[ X_{\text{in}}(t) = \sum_{k=0}^{\infty} A_k P(t - kT) \]

where \( P(t) \) takes the following different forms according to the data pattern:

\[
P(t) = \begin{cases} 
p_{\text{cw}}(t), & \text{if the previous pulse is "1"} 
p_{\text{SLE}}(t), & \text{if the previous pulse is "0"} 
\end{cases}
\]

where \( p_{\text{cw}}(t) \) is the optical power at cw operation, and \( p_{\text{SLE}}(t) \) is the optical pulse function generated by SLE wave modulation as shown in Figure 4.7. This data pattern is chosen because if the previous pulse is "1" the current optical pulse is just a continuation of the previous pulse, i.e., the optical power at cw operation. On the other hand if the previous pulse is "0" the current optical pulse is generated by a SLE wave modulation.

In the rest of this chapter, we examine the pulse broadening effect over a transmission distance \( L \). To include the fiber dispersion effect, we first develop the single-mode fiber model. Based on this model, simulations of chromatic dispersion with both square wave modulation and SLE modulation are performed. We use a sequence of 8 current pulses in the simulation because this sequence gives us all four possible bit patterns, i.e., "1""1", "0""0", "1""0" and "0""1".
5.2 The Single-Mode Fiber Model

Various single-mode fiber models [32][33] have been developed to describe the behavior of propagating optical pulses in a single-mode optical fiber. The most commonly used is the transfer function model in the optical power domain, which is based on the assumption that the optical fiber is a linear system in the that domain [33]. In developing this model, the authors of references [32][33] did not take into account the chirping effects caused by direct modulation, and the fiber input pulses were assumed to be perfect Gaussians. In our study the input pulses are distorted by the chirping effect. Therefore, their model is not valid for our purpose. We will need a new model to illustrate the effect of wavelength chirping on pulse propagation.

Our model is simply based on the fact that different wavelength components of optical pulses propagate at different group velocities in a dispersive optical fiber as discussed in Chapter 2. In the simulation we calculate the time delay for each wavelength component of the fiber input pulses. From Chapter 2 we know that the time delay \( \Delta T \) can be approximated as

\[
\Delta T \approx D(\lambda_f) \cdot \Delta \lambda \cdot L
\]

where the chromatic dispersion term \( D(\lambda_f) \) is assumed to be constant and equal to \( 15 \, \text{ps/(nm} \cdot \, \text{Km)} \) [4] in the simulation. Because the linewidth of the light source is very small, we assume the attenuation \( A \) factor is constant and equal to \( 0.2 \, \text{dB/Km} \) [4].
5.3 Pulse Broadening Analysis

In this section we use the DFB laser diode model (equations 3.3 and 3.4) to generate a series of pulses and transmit the pulses through a dispersive fiber using the fiber model developed in the last section. In the simulation, a sequence of 8-bit (10100011) current pulses (Figures 5.1 and Figure 5.2) with different leading-edges are applied to the rate equations (equations 3.3 and 3.4). The resulting optical pulse sequences are shown in Figure 5.3 and Figure 5.4. Using these pulse sequences as input to the fiber model, we obtain the outputs shown in Figure 5.5 and Figure 5.6 after the pulses are transmitted 100 km. Because of the pulse broadening, the space between the first pulse and the third pulse for the square wave modulation case is significantly reduced, and the bit in-between them is affected. The “0” between the first bit and the third bit may not be detected at the receiver end as a result of this intersymbol interference.

For the SLE wave modulation case, pulse interference is not significant over the same transmission distance. Consequently, SLE wave modulation gives a higher bandwidth-distance product. This conclusion becomes even more obvious if the transmission distance becomes longer. Figure 5.7 shows the pulse broadening as a function of the transmission distance. In the figure, the output pulse width is normalized by the input pulse width.
Figure 5.1: Square wave current sequence.

Figure 5.2: SLE wave current sequence.
Figure 5.3: Optical pulse sequence resulting from square wave modulation.

Figure 5.4: Optical pulse sequence resulting from SLE wave modulation.
Figure 5.5: Broadened optical pulse sequence resulting from square wave modulation.

Figure 5.6: Broadened optical pulse sequence resulting from SLE wave modulation.
Figure 5.7: Pulse-width variation with transmission distance.
CHAPTER 6
Conclusion and Outlook

We have done a preliminary study of wavelength chirping and chromatic dispersion caused by direct intensity modulation of a DFB laser diode.

The unique feedback mechanism of DFB laser diodes has been analyzed theoretically with a simplified model. From the analysis we have shown that DFB laser diodes have narrow linewidth as compared to the F-P laser diodes. We also analyzed the two main contributions to wavelength chirping caused by direct intensity modulation.

We solve the conventional single-mode rate equations of a DFB laser diode numerically using both square wave and SLE wave input pulses. The results show that SLE wave modulation reduces the wavelength chirping; therefore, it decreases the pulse broadening effect. We also concluded that in SLE wave modulation the reduction of chirping effects depended on the width and height of the prepulse. Our calculations showed that the optimal prepulse should have a width of 150 ps and a height of 70.0 mA.
As mentioned in Chapter 3 the conventional single-mode rate equations do not consider the feedback structure of a DFB laser diode. As a result, many phenomena have been neglected in the simple model employed here. For example, because of the longitudinal periodic variation in the DFB laser diode structure, the internal carrier distribution and, therefore, of the power distribution in the active layer may affect the spectral gain profile. This may contribute an additional shift in wavelength. Therefore, the single-mode rate equations are not sufficient for a complete model; and a set of new rate equations which takes into account all the appropriate structural properties is needed for a more accurate analysis of wavelength chirping.
REFERENCES


