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Review on the chirping characteristics of directly modulated laser diodes under high transmission speeds in optical fiber networks

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Abstract

Optical fiber networks are considered an attractive solution for increasing data transmission rates in communication systems. Laser diodes (LDs) are common light sources used to transform electrical signals into optical ones in optical fiber systems. The direct modulation of LDs is preferred as a data transmission technique to decrease power consumption and reduce the overall system cost. However, direct intensity modulation of LDs causes a time variation in the lasing frequency (i.e., frequency modulation). The interdependence between intensity and frequency modulation is referred to as "frequency chirp". We present a review on the effect of laser parameters such as linewidth enhancement factor and nonlinear optical gain suppression on the chirping characteristics of directly modulated LDs under high transmission speeds.

Keywords: Laser diodes, Optical fiber, Chirping characteristics

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1. Introduction

The development of high-speed optical transmission systems is essential to meet the continuous demand for communication networks from subscribers. Optical fiber links are seen as a promising solution for increasing data transmission rates in communication systems. Optical fibers are preferred over electrical links due to their low loss and large bandwidth for long- or short-haul transmission distances (Sector, 2002). With advancements in high-speed optical networks, 40-Gbps optical transmission systems have sparked significant interest for use in very short-distance optical links (Sector, 2002). Laser diodes (LDs) are commonly used as sources of light in optical transmission systems. The electrical signal is used to modulate a laser signal through either direct or external modulation methods (Agrawal, 2012). In direct modulation, the electrical signal is directly applied to the LD with the bias current. This implementation offers low cost and power consumption compared to external modulation (Agrawal, 2012; Dagens et al., 2005). Nevertheless, when LDs are directly modulated with high intensity, there is an accompanying phase modulation caused by the linewidth enhancement factor (α-factor) (Henry, 1986), This phase modulation leads to fluctuations in the lasing frequency over time, commonly referred to as frequency modulation (Agrawal & Dutta, 1986). The relationship between intensity and frequency modulation is known as "frequency chirp"(Agrawal, 2012). In digital transmission systems, lasers with a large differential gain can increase the frequency chirp, which meets the requirement of 40-Gbps short-reach data communication links (Gomatam & DeFonzo, 1988; Yousuf & Najeeb-ud-din, 2018a). The frequency chirp usually results in changes in pulse width and shifts in the output wavelength. The chirping behavior of directly modulated laser diodes is influenced by laser design parameters and operating conditions, resulting in two types of chirp: transient and adiabatic (Ahmed et al., 2012). The chirp appears during the rise/fall of the pulse and originates from turn-on relaxation oscillations. These oscillations result from electron-photon coupling through stimulated emission during steady-state transitions (Arnold & Russer, 1977). On the other hand, the adiabatic chirp refers to the frequency shift between the laser steady-state output powers at "1" and "0" levels (Ahmed et al., 2012). The adiabatic chirp causes a shift in the emitted wavelength, while the transient chirp causes variations in pulse width (del Río Campos & Horche, 2008). The parameters controlling frequency chirps are the linewidth enhancement factor (α-factor) (Henry, 1982; Osinski & Buus, 1987) and the gain suppression coefficient (ε) (Hangauer & Wysocki, 2015; Koch & Linke, 1986; Wang et al., 1993). The α-factor describes how the refractive index changes with the injected carrier density and its effect on LDs' dynamic properties (del Río Campos & Horche, 2012; Vahala et al., 1983). The simultaneous changes in the optical gain and refractive index of the active region, due to the changes in the injected carrier density, result in an intensity-phase coupling. This coupling increases the laser linewidth by a factor of 1 + α2 (Allen, 1994; Henry, 1982; Osinski & Buus, 1987). When the gain suppression coefficient ε is applied, it prevents the carrier density from being tightly clamped above the threshold value. As a result, at high photon densities (S), there is a reduction in the optical gain by a factor of (1 + ε S)-1(Wang et al., 1993). Gain suppression affects carrier-photon resonance, reducing transient chirp and introducing adiabatic chirp through increased damping rate of relaxation oscillations (Abdullah, 2014; Hangauer & Wysocki, 2015). There are several reasons why gain suppression may occur, which include various physical mechanisms. These mechanisms are intraband relaxation processes of injected carriers when the laser is biased above the threshold (Ahmed & Yamada, 1998), spectral hole burning (Adams, 1983), nonlinear absorption (Bowers et al., 1985), carrier diffusion (Furuya et al., 1978), and dynamic carrier heating effects (Gomatam & DeFonzo, 1988). It is important to investigate the effects of laser parameters such as α-factor and gain suppression coefficient ε on frequency chirp induced by directly modulated LDs, particularly at high modulation bit rates. The previous studies (Yousuf & Najeeb-ud-din, 2018b; Yousuf & Najeeb-ud-din, 2016) indicated that increasing ε results in higher adiabatic chirp and lower transient chirp at 5 and 10 Gbps modulation bit rates. However, the findings reported in (Mahmoud, 2007) revealed that the gain suppression causes enhancement in the modulated signal quality at 2 and 10-Gbps. On the other hand, the findings given in (del Río Campos & Horche, 2008) revealed that at 10-Gbps modulation, the adiabatic chirp is the main contributor to the degradation of directly modulated wavelength deviation multiplexing (WDM) system quality. In addition, the findings given in (Mutalip, 2010) confirmed that, in directly modulated WDM systems, frequency chirp reduces the transmission bit rate and vice versa at long fiber lengths. In comparison to the 10-Gbps modulation, Ref. (Sato et al., 2005) showed experimentally and theoretically that at a high modulation bit rate of 40-Gbps, the adiabatic chirp is indistinguishable, and the transient chirp is dominating. Regardless of the chirp type, the findings reported in (Albeladi et al., 2013; Peral et al., 1998) showed that at high-speed modulation, the laser chirp is combined with the fiber dispersion in such a way to limit the fiber length. Although most of these previous studies focused on the impact of laser chirp on the system performance, there is still room for a more in-depth investigation into the influence of laser design and structure parameters (α-factor and ε) on the frequency chirp and its effects on the fiber length, especially at a high modulation bit rates. In addition, it is important to study on the influence of these laser parameters on the shifting of the output wavelength away from the actual laser wavelength, which is a critical issue in WDM system performance avoiding the channel interference (del Río Campos & Horche, 2008, 2012; del Río Campos et al., 2010). This article presents a review on the effect of laser parameters such as linewidth enhancement factor and nonlinear optical gain suppression on the chirping characteristics of directly modulated LDs under high transmission bit rates. The basic operation, different structures, and the direct modulation technique of LDs are addressed in Section 2. The chirping characteristics of directly modulated LDs are illustrated in Section 3, and the conclusions appear in Section 4.

2. Basic operation of LD

Laser diode LD is a common light source to transform electrical signals into optical signals in optical fiber communication links. In 1962, Robert Hall operated the first PN junction laser (GaAs laser) at low temperatures at 4.2°k (Hall et al., 1962; Nathan et al., 1962; Quist et al., 1962). Nevertheless, the technology was not yet advanced enough to achieve laser action at higher levels such as room temperatures. This problem was nearly solved by Herbert Kroemer (Ujager et al., 2010) in 1963 when using double heterostructures. This allowed the production of low-cost, commercially available LDs, revolutionizing optical communication. Continuous oscillation at room temperature was achieved in 1970 (Hayashi et al., 1970; Lockwood et al., 1970; Suhara, 2004). Since then, notable developments have occurred in various fields of science and technology. Nowadays, LDs have been used practically as one of the most significant optoelectronic devices and are extensively used in a variety of applications in several areas (Casey & Panish, 1978; Chow et al., 2012; Coldren et al., 2012; Ito & Nakamura, 1989; Kressel, 2012). LDs have many characteristics, such as ability of direct modulation, small size, and emission frequencies in the infrared communication range (Azadeh, 2009). These benefits made the LD one of the most important optical sources in optical fiber communication system.

Any laser device must have three essential components: medium that provides gain (amplification), pump source, which is a type of external energy that causes population inversion, and cavity mirrors that confines the optical field (Pol, 2002). The amplifying medium in the simplest LDs is a PN junction made of direct band gap semiconductor materials (i.e. the energy minimum of the conduction band and the energy maximum of the valence band happen at the same momentum), as a result, there is a high chance of the transition occurring, which makes it easy to emit light (Suhara, 2004). The most common semiconductor materials used are those made by combining elements from III/V groups of the periodic table, such as GaAs, AlGaAs, InGaAs, and InGaAsP, depending on the required lasing wavelength (Agrawal & Dutta, 1993). When the PN junction is formed, several physical phenomena can occur. The most important one is the formation of PN barrier due to the potential difference between the P-type and the N-type layers (Sze, 1981). This barrier generates an electrical field (E), which induces the formation of a depletion region at the PN boundary. The width of the formed depletion region depends on the doping concentrations of P-type and N-type (Sze, 1981). Thus, in order to operate the laser, a forward-bias current must be applied to overcome this barrier, which act as an electrical pump source for laser operation.

When the LD is pumped with low current (I), the number of electrons in the valence band (VB) is much greater than that in the conduction band (CB). When I is increased, more electrons are introduced into the CB, increasing the radiative recombination rate. That is, the conduction electrons in the CB recombine with empty states (holes) in the VB, releasing excess energy as photons (Farghal, 1999). The dominant process of photon production in this case is spontaneous emission that happens without any stimulation and propagates in all directions within the cavity (Allen, 1994). When an incoming photon from spontaneous emission induces an excited electron in the CB to transition to the VB, a new photon with the same energy and momentum as the incident photon is emitted.

This process is known as "stimulated emission"(Farghal, 1999). At a specific current known as the "transparency current (Io)", a portion of the spontaneously generated photons that are transmitting nearly parallel to the cavity axis are amplified by stimulated emission, and the net gain begins to increase. However, some photons are lost through the partially transmitted facets while others are absorbed or scattered within the cavity. When I is even more increased, a population inversion occurs, the active area displays an optical gain (g), and it is then able to amplify the light that is traveling through it. When I reaches the threshold value (Ith), g equals the losses, and stimulated emission starts to take over. The "threshold gain (gth)" is the minimum amount of gain g required for laser operation and is given by (Farghal, 1999).

$$g_{th} = \alpha_{\text{int}} + \alpha_{mir} = \alpha_{\text{int}} + \frac{1}{\quad} \ln(\frac{1}{R_f R_b})$$

(2-1)

where αint and αmir are the losses in the active area and at the mirrors, respectively. The power reflectivities at the front and back facets are denoted by Rf and Rb, respectively, and L is the active layer length.

Above threshold, the stimulated emission dominates, and the device emits laser light. The number of photons then increases rapidly at expense of the number of electrons N. Therefore, the number of electrons increases just a little above its threshold value Nth. Fig. (2-1) schematic illustration of the characteristic of optical gain g versus injection current I. The figure shows that the net gain g begins to increase linearly with I at the transparency current Io, which is below the threshold value Ith (refer to the basic operation of LD in section 2.2.2). When the laser operates above threshold, g is suppressed and clamped just under gth due to the gain suppression effect. The gain suppression reasons can be attributed to many physical mechanisms, including intraband relaxation processes of injected carriers when the laser is biased above threshold (Ahmed & Yamada, 1998), spectral hole burning (Adams, 1983), nonlinear absorption (Bowers et al., 1985), carrier diffusion (Furuya et al., 1978), and dynamic carrier heating effects (Gomatam & DeFonzo, 1988).

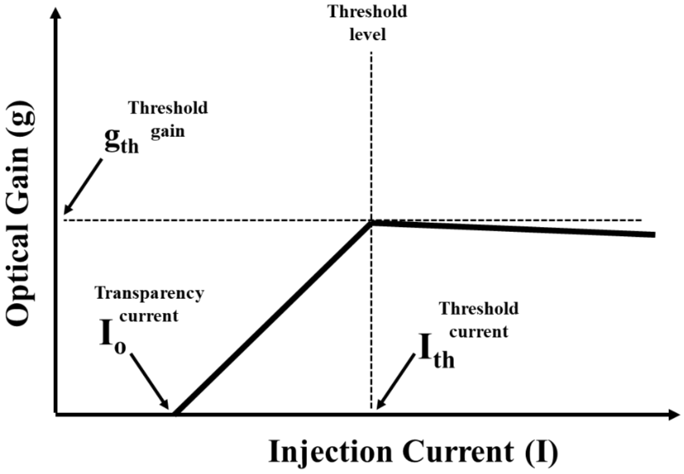

Fig. (2-1): Scheme of variation of optical gain *g* with injection current *I*.

The phase condition determines the frequency of the laser light (ν_{laser}), which requires the optical wave to be reflected in phase after completing a round-trip in the cavity and is given by (Farghal, 1999)

$$\nu_{laser} = \nu_q = \frac{qc}{2n_{activ}L}, \qquad q = 1,\ 2,\ 3,\ \ldots.. \tag{2-2}$$

where vq is the longitudinal cavity mode frequency, nactiv represents the refractive index of the active layer, and c is the speed of light in vacuum. This equation indicates that one of the longitudinal mode frequencies must match the laser frequency vlaser to satisfy the phase condition (Farghal, 1999). Then the output power increases by many orders of magnitude for a slight increase in the current I, as illustrated in fig. (2-2) of light output versus current (L-I) characteristics. When the threshold is exceeded, the laser nearly increases linearly with the current (Allen, 1994).

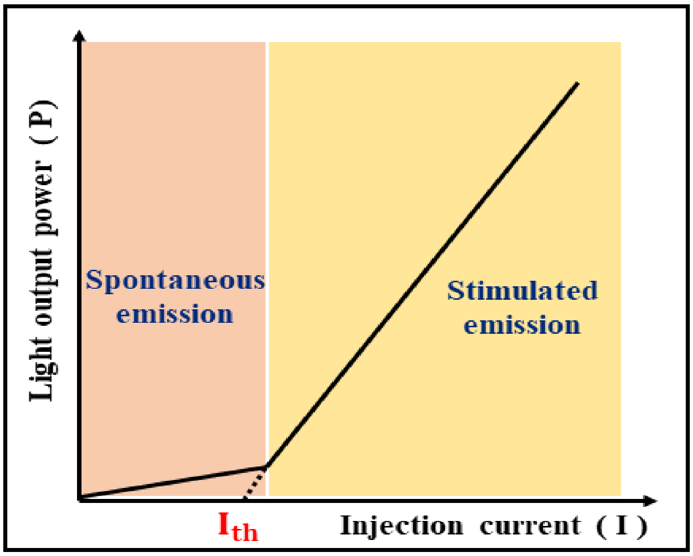

Fig. (2.2): Common (L-I) characteristics of laser diode.

The performance of LDs is improved when the active layer is confined between two cladding semiconductors with relatively larger band gaps (Alferov, 2002; Kroemer, 1963). These lasers are known as double-heterostructure (DH) lasers whose basic operation is illustrated in fig. (2-3). Potential barriers resulting from the bandgap offsets prevent the electrons and holes injected into the active area from passing into the cladding layers. The other important advantage of the cladding layers is that they have a lower refractive index than that of the active area, causing light confinement. The recombination rate increases with such a structure, which in turn reduces the threshold current density as a result of the restriction of both light and charge carriers in the thin active area. The laser threshold current density reaches 0.5 kA/cm2 in AlGaAs DH lasers with a thin (≈ 0.1 µm thick) active layer (Ahmed & El-Lafi, 2008).

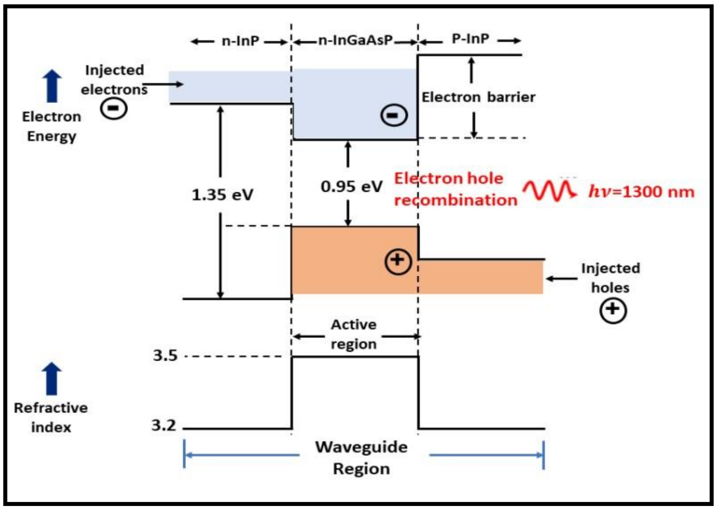

Fig. (2-3): Energy band and refractive index diagram of a double- heterostructure LD at forward bias.

2.1. Structures of LD

Although the basic operation of most LDs is as stated above, each LD has a different internal structure. There are various methods for reflecting light back into the laser cavity to produce the desired positive feedback. Based on LD structures, there are several LD types, each of which may be good for a specific application. The simplest LD structure is the Fabry-Perot (FP) laser, in which the resonator is created by placing the active gain medium between two mirrors. Fig. (2-4) shows the basic structures of FP lasers. The active gain medium is composed of a thin layer ($\approx 0.1\ \mu$m) of a direct band gap semiconductor material such as GaAs inserted between P-type and N-type cladding layers of a semiconductor with a larger bandgap such as AlGaAs. The mirrors of this type are formed by cleaved facets, which have a reflectivity of 30% when left uncoated. The amount of light ejected from the front facet can be increased by applying high reflectivity (HR) coating to the back facet (typically > 90 %) and low reflectivity (LR) coating to the front facet (typically 10 to 30 %) (O'Carroll, 2013). Both sides of the cavity emit laser light, however only the light from the front facet is used as an output beam. The radiation emitted from the opposite (back) end of the laser could be used to monitor its output (Hall et al., 1962).

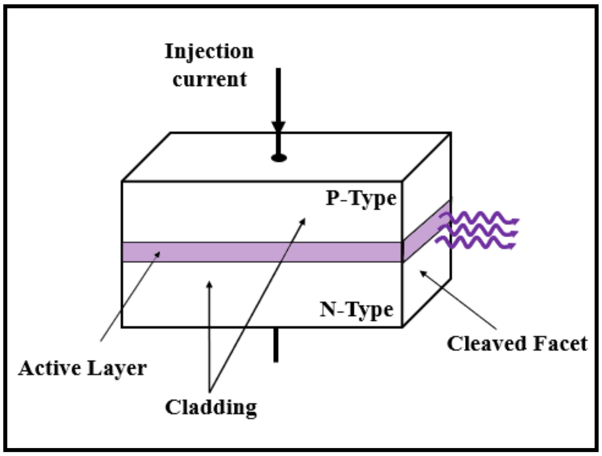

Fig. (2-4): Schematic diagram of the basic structure of FP laser.

The emission in FP laser is generated at the cavity longitudinal modes and can be tuned by adjusting the cavity length (Lcav) (Dutton, 1998). FP lasers typically generate a multimode spectrum as illustrated in fig. (2-5). The spectral modes are spaced equally in frequency ν by:

$$\Delta \nu = \frac{c}{2n_a L_{cav}} \tag{2-3}$$

where c is the speed of light, and na is the active layer refractive index (Buus, 1990). FP lasers can be used to transmit data over multimode fiber, but their high dispersion induced by the wide spectral line of up to 5 nm limits them from being used for long distances (Woodward & Husson, 2006). FP lasers are a highly developed technology and are available for a wide range of commercial applications (Lee & Won, 2004).

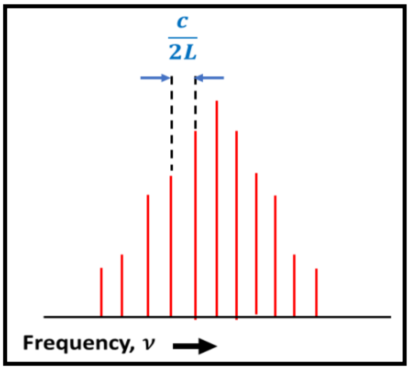

Fig. (2-5): The output longitudinal-mode spectrum of the FP laser.

The distributed feedback (DFB) laser was developed during the 1980s and has become the most common single-mode laser used in fiber optic communications and routinely for WDM systems (Lo & Ghafouri-Shiraz, 1995). In DFB lasers, a corrugated grating is etched along the entire length of the cavity to achieve a single-mode operation (Coldren et al., 2012). Fig. (2-6) shows a schematic diagram for the structure and operation of the DFB lasers. The grating provides the reflections required for laser operation; however, unlike facet mirrors, the grating is designed to provide a selective reflection at one specific wavelength known as the Bragg wavelength (λBragg).

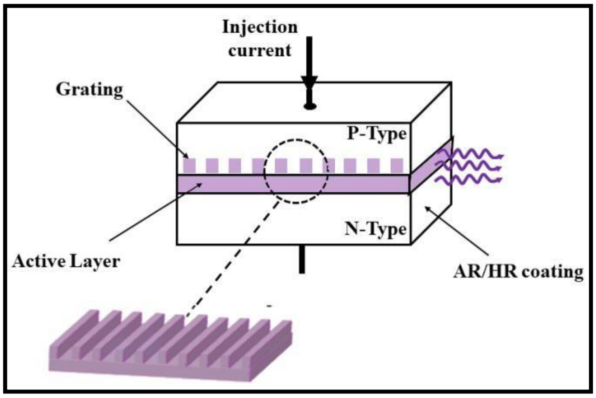

Fig. (2-6): Diagram presenting the main components of a DFB laser.

The reflection, or feedback, is achieved by Bragg diffraction, a phenomenon that couples the waves spreading in the forward and reverse directions within the cavity. Coupling occurs only if the Bragg condition is fulfilled at the wavelength (Lu, 2010), where Λ is the grating period, and m represents the grating order.

$$\lambda_{Bragg} = \frac{2n_a\Lambda}{m} \tag{2-4}$$

Each grating scatters and reflects the incident light rays as a result of internal reflections. When the period of the grating is equal to $\Lambda = m\lambda_{Bragg} \; | 2n_a$, only the mode with $\lambda =$

λ_{Bragg} is reflected constructively and emit the single- mode laser. The other modes exhibit higher losses and are suppressed from oscillation(Lu, 2010). The output spectrum of DFB laser is typically illustrated in fig. (2-7). When $m = 1$ and $n_a = 3.3$, for a DFB laser operating at = 1550 nm, Λ is approximately 235 nm (Lu, 2010).

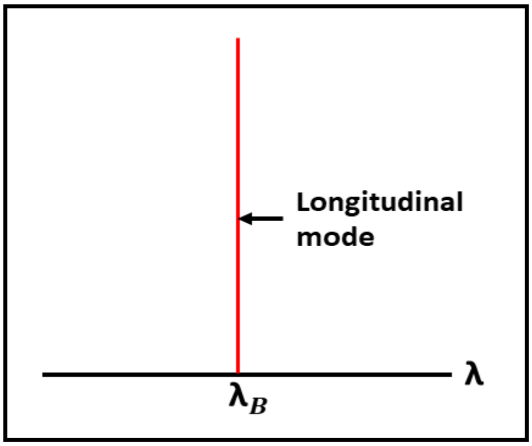

Fig. (2-7): The output longitudinal-mode spectrum of the DFB laser

DFB lasers offer narrow spectral lines (Hunsperger & Meyer-Arendt, 1992), less chirp (Ohtsubo, 2008), and enhanced wavelength selectivity when compared to the FP lasers. These advantages make them perfect for high-performance systems that need single-mode emissions (Woodward & Husson, 2006). However, controlling the emission wavelength close to the required one is difficult (Carroll et al., 1998).

The quantum well (QW) laser has emerged as a new type of semiconductor laser in recent years, which is invented to enhance the speed of the laser (Van der Ziel et al., 1975). Except for the thickness of the active layer, it is nearly identical to a typical double heterostructure laser. The simplest QW laser can be constructed by inserting a thin layer of one type of semiconductor material between two layers of another with a different band-gap. The main idea of QW lasers is as follows. Conduction electrons are restricted in the active layer due to differences in the potential energies of the QW materials, and the two enclosing higher energy materials act as a barrier for these electrons as shown in fig. (2-8a) (Kim, 2005). Quantized energy levels are then created in the active layer as a result of the density of states, which is step-like in QWs (Haji, 2012). This indicates that a high concentration of electrons can be produced easily at the well interfaces and increases quickly as the current is increased. Therefore, compared to bulk materials, population inversion is achieved at much lower energies, which results in lower threshold currents and better thermal properties (Haji, 2012). When the electron and hole states are fully inverted, the gain in a well will saturate due to limited energy levels (Silfvast, 2004). This can be solved by employing multiple QWs (MQWs) (Park & Zory, 1993) as shown schematically in fig. (2-8b). The MQWs enhance the optical confinement in the active material while also providing a higher gain, reducing the threshold current (Yvind et al., 2004). MQW lasers achieve higher gain when compared to the typical double heterostructure lasers (Ohtsubo, 2008). Additional advantages include lower optical losses, better carrier confinement that results in lower leakage currents, high modulation speed, and reduced temperature dependence (Ujager et al., 2010). Due to higher flexibility in manufacturing, QW technology may become the leading technology for high-performance semiconductor devices in the future (Katsuyama, 2009).

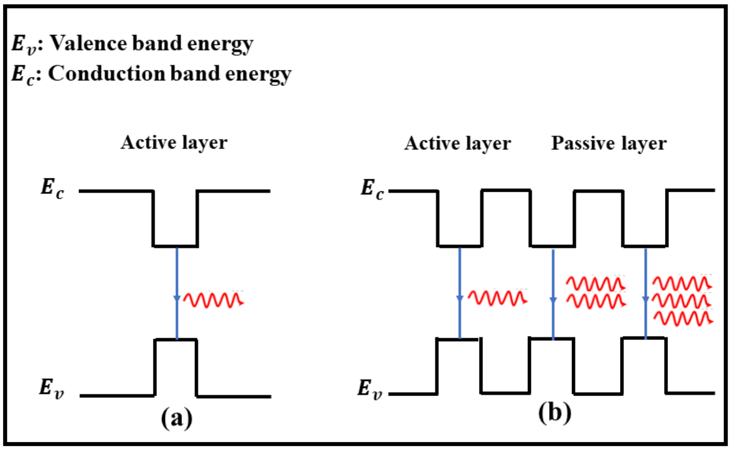

Fig. (2-8): Energy bands diagram for the three different kinds of quantum well structures a) QW, and b) MQW

2.2. Direct modulation of LDs

The transferred data in communication systems is typically available as an electrical signal that can be either analog or digital form. The analog signal changes over time constantly. In contrast, the digital signal can only take a few discrete values, such "1" and "0" in binary encoding. To make the laser light carry a signal, modulation must be introduced into the light to represent the signal. The electrical signal is applied either directly to the LD or to an external modulator. The LD has the ability to directly modulate digital signals by changing the current. High light-current linearity is a feature of the laser. As a result, the laser is ideal for modulation over a broad frequency range up to tens of GHz (Kjebon et al., 1997). Direct current modulation of LDs is a low-cost technique that reduces the need for electrical circuitry when compared to other external modulation methods. The external modulation method use continuous-wave lasers coupled with electro-optic modulators, or integrated electro-absorption modulators, which are relatively complicated devices and consume high power (Lipson et al., 1990; O'Carroll, 2013). The direct modulation response of LDs can be studied by substituting the DC term in the rate equation (2-5) of N(t) with a time-dependent current of the form (Petermann, 1991)

$$I\,(t) = I_b + I_m \psi_{m(}(t) \tag{2-5}$$

where I_b is the bias current, I_m the modulation current, and Ψ_m (t) represents the current signal form. In digital modulation, $\Psi_m(t)$ is a time-varying function with a level of "0" or "1" that describes the bit format of the modulating current. In a binary electrical pulse train, information is often represented using the non-return to zero (NRZ) format, which is often widely applied in data transmission systems due to its ease of generation (Yin et al., 2010). Fig. (2-9) illustrates the basic idea of direct modulation of a digital signal. The time-varying modulating current signal is converted to a time-varying modulating laser pulse.

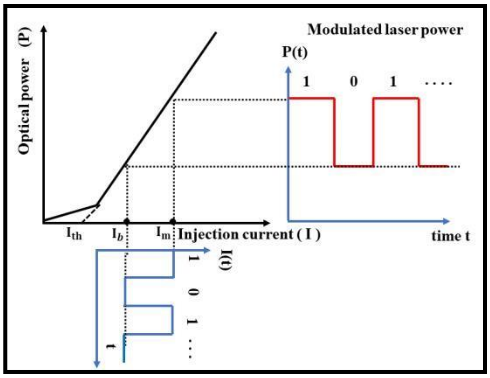

Fig. (2-9): The concept of direct digital modulation of LD.

3. Chirping characteristics of direct modulation of LDs

Although the direct intensity modulation of LDs provides various desired properties, however, it results in a simultaneous phase modulation through the linewidth enhancement factor (α-factor) (Henry, 1986). This phase modulation causes a time variation in the lasing frequency (i.e., frequency modulation) (Agrawal & Dutta, 1986). The interdependence between intensity and frequency modulation is referred to as "frequency chirp" (Agrawal, 2012). The increase of frequency with the time is known as "up-chirp" or "blue shift", whereas the decrease of frequency with the time is known as "down-chirp" or "red shift" as illustrated in fig. (3-1).

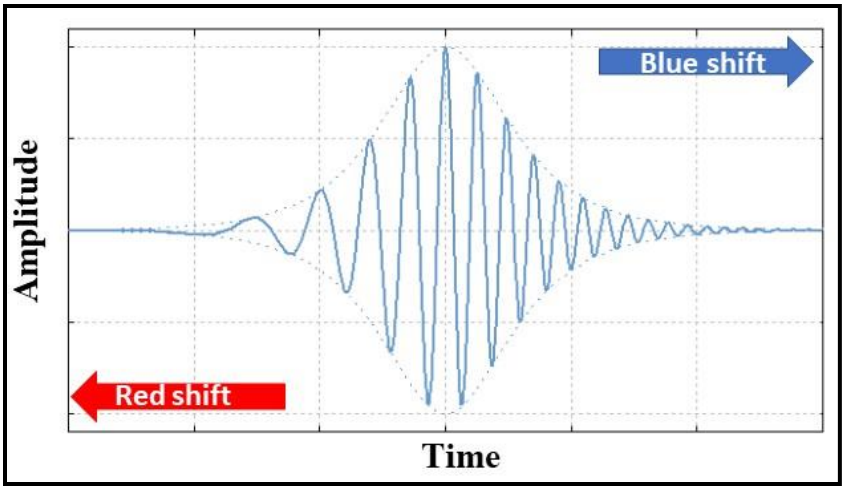

Fig. (3-1): Illustration of blue and red shifts of frequency chirp.

The time-dependent optical frequency variation (chirp) within the active region of a directly large signal modulation of single mode LD can be obtained from the phase rate equation as

$$\Delta\nu = \frac{1}{2\pi}\left(\frac{d\varphi}{dt}\right) \tag{3-1}$$

The frequency chirp can be obtained also in terms of the modulated laser output optical power as (Koch & Bowers, 1984; Tomkos et al., 2001; Tucker, 1985):

$$\Delta\nu = \frac{\alpha}{4\pi}\left\{\frac{d}{dt}[\ln P(t)] + kP(t)\right\}, \tag{3-2}$$

where α is the linewidth enhancement factor and k is the adiabatic coefficient. The frequency chirp typically causes variations in pulse width, which combined with the fiber dispersion to degrade the digital system performance (Ahmed et al., 2014; del Río Campos et al., 2011; Hakki, 1992; Tucker, 1985; Yamamoto et al., 1987). Another serious limitation of frequency chirp is that it causes shifting in the output wavelength away from the actual laser wavelength, which is a critical issue in the directly modulated WDM systems in order to avoid channel interference (del Río Campos & Horche, 2008).

The chirping behavior of directly modulated LDs is characterized by two chirp types: transient and adiabatic chirp, which are influenced by laser design parameters and operating conditions (Ahmed et al., 2012). The transient chirp appears around the rise/fall locations of the pulse and originates from the turn-on relaxation oscillations. These relaxation oscillations occur as a result of electron-photon coupling through stimulated emission during the transition between steady states (Arnold & Russer, 1977). On the other hand, the adiabatic chirp is the frequency offset induced between laser steady-state output powers (around the mean values in both "1" and "0" levels) (Ahmed et al., 2012). The transient chirp causes variations in pulse width, whereas the adiabatic chirp induces shift in the emitted wavelength (del Río Campos & Horche, 2008). The transient chirp is represented in the first term of equation (2-11), and it has a significant value during the relaxation oscillations of the laser. This indicates that devices with strong damping relaxation oscillations exhibit good transient chirp characteristics resulting from the reduction in the rate of change of *lnP(t)*. The second term of equation (2-11) represents the adiabatic chirp, which arises from spontaneous emission and gain suppression effects, and is associated with the frequency offset between the ‘‘1’’ and ‘‘0’’ power levels during the modulation.

The laser design and structure parameters that control these types of frequency chirp are the linewidth enhancement factor (α-factor) (Henry, 1982; Osinski & Buus, 1987) and the gain suppression coefficient (ε) (Hangauer & Wysocki, 2015; Koch & Linke, 1986; Wang et al., 1993). The α-factor quantifies the variations of the refractive index and gain with the carrier density N inside the cavity, and describes their effect on the dynamical properties of LD using the following equation (Henry, 1982):

$$\alpha = -\frac{4\pi}{\lambda}\left(\frac{\partial n / \partial N}{\partial g / \partial N}\right) \qquad (3\text{-}3)$$

where n is the refractive index of the active region, g is the gain per unit length, and λ is the emitted laser wavelength. The changes in the injected carrier density induce simultaneous changes in the optical gain and refractive index of the active region, resulting in an intensity-phase coupling, which increases the laser linewidth by a factor of $1 + \alpha^2$ (Allen, 1994; Henry, 1982; Osinski & Buus, 1987). The adiabatic coefficient k depends on the laser structure and is directly related to the nonlinear gain suppression coefficient ε through the following expression (Tucker, 1985):

$$k = \frac{2\Gamma}{V\eta_o h\nu}\varepsilon \qquad (3\text{-}4)$$

It is worth noting that the gain suppression mentioned above affects carrier-photon resonance suppression and thus increases the damping rate of relaxation oscillations, reducing transient chirp and introducing adiabatic chirp (Abdullah, 2014; Hangauer & Wysocki, 2015).

4. Conclusion

The review presented a simulation study on the effect of laser parameters (linewidth enhancement factor α and the gain suppression coefficient ε) on the chirping characteristics of directly modulated high-speed quantum well-DFB laser diode and assess its performance for use in 40-Gbps optical fiber links. The chirp characteristics include the modulated signal waveform, frequency peak- to-peak chirp, and laser output wavelength spectrum. As α increases, the modulated laser waveform shows relaxation oscillations in "1" or "0" bits with peak overshoots and increased peak-to-peak chirp due to transient chirp. Increasing ε induces adiabatic chirp and dampens out overshoots, which slightly reduces the transient chirp and in turn reduces the peak-to-peak chirp when α increases, creating a difference between "1" and "0" levels. Although ε works to reduce the laser peak-to-peak chirp (i.e., improve the chirp characteristics), it causes significant shifts in the lasing wavelength Δλ relative to the actual laser wavelength, degrading the efficiency of LD for use in optical fiber communication systems. As the value of ε increases, the performance of the fiber link improves. On the other hand, increasing the α-factor has a negative effect on the performance of the fiber link. With an increase in fiber length, the impact of α and ε on chirp characteristics becomes more pronounced. The maximum predicted fiber length (Lmax) decreases with an increase in α or a decrease in ε.

References

Abdullah, R. A. J. O. (2014). The influence of gain suppression on dynamic characteristics of violet InGaN laser diodes. *125*(1), 580-582.

Adams, M. J. E. L. (1983). Influence of spectral hole-burning on quaternary laser transients. *16*(19), 627-628.

Agrawal, G. P. (2012). *Fiber-optic communication systems*. John Wiley & Sons.

Agrawal, G. P., & Dutta, N. K. (1986). *Long-wavelength semiconductor lasers* (Vol. 1). Springer.

Agrawal, G. P., & Dutta, N. K. (1993). Distributed-feedback semiconductor lasers. In *Semiconductor Lasers* (pp. 319-384). Springer.

Ahmed, M., & El-Lafi, A. J. P. (2008). Analysis of small-signal intensity modulation of semiconductor lasers taking account of gain suppression. *71*(1), 99-115.

Ahmed, M., Mahmoud, S. W., & Mahmoud, A. A. J. P. (2012). Influence of pseudorandom bit format on the direct modulation performance of semiconductor lasers. *79*(6), 1443-1456.

Ahmed, M., & Yamada, M. J. J. o. A. P. (1998). An infinite order perturbation approach to gain calculation in injection semiconductor lasers. *84*(6), 3004-3015.

Ahmed, M. F., Bakry, A. H., Albelady, F. T. J. A. J. f. S., & Engineering. (2014). Digital modulation characteristics of high-speed semiconductor laser for use in optical communication systems. *39*(7), 5745-5752.

Albeladi, F. T., Ahmed, M. F., & Bakry, A. H. (2013). Performance evaluation of 40 gb/s directly-modulated optical fiber communication systems. 2013 Saudi International Electronics, Communications and Photonics Conference,

Alferov, Z. I. (2002). The history of heterostructure lasers. In *Nano-Optoelectronics* (pp. 3-22). Springer.

Allen, J. (1994). Semiconductor lasers, GP Agrawal and NK Dutta. 2nd edn. Van Nostrand Reinhold, New York, 1993. ISBN 0 442 01102 4,£ 66.00. No. of pages 616. In: Wiley Online Library.

Arnold, G., & Russer, P. J. A. p. (1977). Modulation behavior of semiconductor injection lasers. *14*(3), 255-268.

Azadeh, M. (2009). *Fiber optics engineering*. Springer.

Bowers, J., Koch, T. L., Hemenway, B., Wilt, D., Bridges, T., & Burkhardt, E. J. E. l. (1985). High-frequency modulation of 1.52 μm vapour-phase-transported InGaAsP lasers. *9*(21), 392-393.

Buus, J. J. T., SPIE Optical Engineering Press, Bellingham, Wash, USA,. (1990). Single frequency semiconductor lasers, vol.

Carroll, J. E., Whiteaway, J., Plumb, D., & Plumb, R. (1998). *Distributed feedback semiconductor lasers* (Vol. 10). IET.

Casey, H. C., & Panish, M. B. (1978). *Heterostructure lasers* (Vol. 1). Academic press.

Chow, W. W., Koch, S. W., & Sargent, M. I. (2012). *Semiconductor-laser physics*. Springer Science & Business Media.

Coldren, L. A., Corzine, S. W., & Mashanovitch, M. L. (2012). *Diode lasers and photonic integrated circuits*. John Wiley & Sons.

Dagens, B., Martinez, A., Make, D., Le Gouezigou, O., Provost, J.-G., Sallet, V., Merghem, K., Harmand, J.-C., Ramdane, A., & Thedrez, B. J. I. p. t. l. (2005). Floor free 10-gb/s transmission with directly modulated gainnas-gaas 1.35-/spl mu/m laser for metropolitan applications. *17*(5), 971-973.

del Río Campos, C., & Horche, P. R. (2008). Directly modulated laser intrinsic parameters Optimization for WDM Systems. 2008 International Conference on Advances in Electronics and Micro-electronics,

del Río Campos, C., & Horche, P. R. (2012). *Effects of Dispersion Fiber on CWDM Directly Modulated System Performance*. IntechOpen.

del Río Campos, C., Horche, P. R., & Martin-Minguez, A. J. O. c. (2010). Analysis of linewidth and extinction ratio in directly modulated lasers for performance optimization in 10 Gbit/s CWDM systems. *283*(15), 3058-3066.

del Río Campos, C., Horche, P. R., & Minguez, A. M. (2011). Interaction of semiconductor laser chirp with fiber dispersion: Impact on WDM directly modulated system performance. Proceedings of The Fourth International Conference on Advances in Circuits, Electronics and Micro-electronics, CENICS,

Dutton, H. J. (1998). *Understanding optical communications* (Vol. 1). Prentice Hall PTR New Jersey.

Farghal, A. H. M. (1999). *Studies on device performance of optical filters and semiconductor lasers for optical communications* 金沢大学].

Furuya, K., Suematsu, Y., & Hong, T. J. A. o. (1978). Reduction of resonancelike peak in direct modulation due to carrier diffusion in injection laser. *17*(12), 1949-1952.

Gomatam, B. N., & DeFonzo, A. P. J. J. o. a. p. (1988). Gain suppression in semiconductor lasers: The influence of dynamic carrier temperature changes. *64*(3), 1555-1557.

Haji, M. (2012). *Optical code division multiple access systems in AlGaInAs/InP* University of Glasgow].

Hakki, B. W. J. J. o. l. t. (1992). Evaluation of transmission characteristics of chirped DFB lasers in dispersive optical fiber. *10*(7), 964-970.

Hall, R. N., Fenner, G. E., Kingsley, J., Soltys, T., & Carlson, R. J. P. R. L. (1962). Coherent light emission from GaAs junctions. *9*(9), 366.

Hangauer, A., & Wysocki, G. J. I. J. o. S. T. i. Q. E. (2015). Gain compression and linewidth enhancement factor in mid-IR quantum cascade lasers. *21*(6), 74-84.

Hayashi, I., Panish, M., Foy, P., & Sumski, S. J. A. P. L. (1970). Junction lasers which operate continuously at room temperature. *17*(3), 109-111.

Henry, C. J. I. J. o. Q. E. (1982). Theory of the linewidth of semiconductor lasers. *18*(2), 259-264.

Henry, C. J. J. o. L. T. (1986). Phase noise in semiconductor lasers. *4*(3), 298-311.

Hunsperger, R. G., & Meyer-Arendt, J. R. J. A. O. (1992). Integrated optics: theory and technology. *31*(3), 298.

Ito, R., & Nakamura, M. J. B., Tokyo. (1989). Semiconductor Lasers [Fundamentals and Application].

Katsuyama, T. J. S. T. R. (2009). Development of semiconductor laser for optical communication. *69*, 13-20.

Kim, J. H. (2005). *Wide-band and scalable equivalent circuit model for multiple quantum well laser diodes*. Georgia Institute of Technology.

Kjebon, O., Schatz, R., Lourdudoss, S., Nilsson, S., Stålnacke, B., & Bäckbom, L. J. E. L. (1997). 30GHz direct modulation bandwidth indetuned loaded InGaAsP DBR lasers at1. 55 µm wavelength. *33*, 488-489.

Koch, T., & Linke, R. J. A. P. L. (1986). Effect of nonlinear gain reduction on semiconductor laser wavelength chirping. *48*(10), 613-615.

Koch, T. L., & Bowers, J. E. J. E. l. (1984). Nature of wavelength chirping in directly modulated semiconductor lasers. *20*(25), 1038-1040.

Kressel, H. (2012). *Semiconductor lasers and herterojunction LEDs*. Elsevier.

Kroemer, H. J. P. o. t. I. (1963). A proposed class of hetero-junction injection lasers. *51*(12), 1782-1783.

Lee, H.-J., & Won, Y.-H. J. J. o. t. O. S. o. K. (2004). External optical modulator using a low-cost Fabry-Perot laser diode for optical access networks. *8*(4), 163-167.

Lipson, J., Upadhyayula, L., Huang, S.-Y., Roxlo, C. B., Flynn, E., Nitzsche, P., McGrath, C. J., Fenderson, G. L., Schaefer, M. S. J. I. t. o. m. t., & techniques. (1990). High-fidelity lightwave transmission of multiple AM-VSB NTSC signals. *38*(5), 483-493.

Lo, B., & Ghafouri-Shiraz, H. J. J. o. l. t. (1995). Spectral characteristics of distributed feedback laser diodes with distributed coupling coefficient. *13*(2), 200-212.

Lockwood, H., Kressel, H., Sommers Jr, H., & Hawrylo, F. J. A. P. L. (1970). An efficient large optical cavity injection laser. *17*(11), 499-502.

Lu, H.-H. J. P. n. T. (2010). Fibre broadband network systems.

Mahmoud, S. W. J. E. J. S. (2007). Influence of gain suppression on static and dynamic characteristics of laser diodes under digital modulation. *30*, 237-251.

Mutalip, Z. B. A. (2010). Frequency chirp characteristics on WDM direct modulation. 2010 Second International Conference on Computer Engineering and Applications,

Nathan, M. I., Dumke, W. P., Burns, G., Dill Jr, F. H., & Lasher, G. J. A. P. L. (1962). Stimulated emission of radiation from GaAs p-n junctions. *1*(3), 62-64.

O'Carroll, J. (2013). *Novel optical transmitters for high speed optical networks* Dublin City University].

Ohtsubo, J. J. S. S. I. O. S. (2008). Semiconductor Lasers Stability, Instability and Chaos Second, Enlarged Edition. *111*.

Osinski, M., & Buus, J. J. I. J. o. Q. E. (1987). Linewidth broadening factor in semiconductor lasers--An overview. *23*(1), 9-29.

Park, Y., & Zory, P. (1993). Temperature dependence of the threshold current density of CdZnSe blue-green quantum well diode lasers. Proceedings of LEOS'93,

Peral, E., Marshall, W. K., & Yariv, A. J. J. o. l. t. (1998). Precise measurement of semiconductor laser chirp using effect of propagation in dispersive fiber and application to simulation of transmission through fiber gratings. *16*(10), 1874.

Petermann, K. (1991). *Laser diode modulation and noise* (Vol. 3). Springer Science & Business Media.

Pol, J. M. (2002). *Semiconductor Laser Dynamics: Compound–cavity, polarization and transverse modes* PhD thesis. de la Universitat de les Illes Balears. per optar al grau de …].

Quist, T. M., Rediker, R. H., Keyes, R., Krag, W., Lax, B., McWhorter, A. L., & Zeigler, H. J. A. P. L. (1962). Semiconductor maser of GaAs. *1*(4), 91-92.

Sato, K., Kuwahara, S., & Miyamoto, Y. J. J. o. L. t. (2005). Chirp characteristics of 40-Gb/s directly modulated distributed-feedback laser diodes. *23*(11), 3790.

Sector, I. T. S. (2002). ITU-T G. 693: Transmitter eye mask and reference receiver proposal for serial 40G. In: January.

Silfvast, W. T. (2004). *Laser fundamentals*. Cambridge university press.

Suhara, T. (2004). *Semiconductor laser fundamentals*. CRC press.

Sze, S. J. P. o. S. D. S. e. (1981). Tunnel devices.

Tomkos, I., Roudas, I., Hesse, R., Antoniades, N., Boskovic, A., & Vodhanel, R. J. O. c. (2001). Extraction of laser rate equations parameters for representative simulations of metropolitan-area transmission systems and networks. *194*(1-3), 109-129.

Tucker, R. S. J. I. t. o. e. d. (1985). High-speed modulation of semiconductor lasers. *32*(12), 2572-2584.

Ujager, F. S., Zaidi, S., & Younis, U. (2010). A review of semiconductor lasers for optical communications. 7th International Symposium on High-capacity Optical Networks and Enabling Technologies,

Vahala, K., Chiu, L., Margalit, S., & Yariv, A. J. A. P. L. (1983). On the linewidth enhancement factor α in semiconductor injection lasers. *42*(8), 631-633.

Van der Ziel, J., Dingle, R., Miller, R. C., Wiegmann, W., & Nordland Jr, W. J. A. P. L. (1975). Laser oscillation from quantum states in very thin GaAs− Al0. 2Ga0. 8As multilayer structures. *26*(8), 463-465.

Wang, G., Nagarajan, R., Tauber, D., & Bowers, J. J. I. p. t. l. (1993). Reduction of damping in high-speed semiconductor lasers. *5*(6), 642-645.

Woodward, B., & Husson, E. B. (2006). *Fiber optics installer and technician guide*. John Wiley & Sons.

Yamamoto, S., Kuwazuru, M., Wakabayashi, H., & Iwamoto, Y. J. J. o. l. t. (1987). Analysis of chirp power penalty in 1.55-µm DFB-LD high-speed optical fiber transmission systems. *5*(10), 1518-1524.

Yin, A., Li, L., & Zhang, X. J. O. (2010). Analysis of modulation format in the 40 Gbit/s optical communication system. *121*(17), 1550-1557.

Yousuf, A., & Najeeb-ud-din, H. J. J. o. O. (2018a). Investigation on chirping characteristics of a 1.55-µm directly modulated distributed feedback laser. *47*, 481-488.

Yousuf, A., & Najeeb-ud-din, H. J. J. o. O. (2018b). Investigation on chirping characteristics of a 1.55-µm directly modulated distributed feedback laser. *47*(4), 481-488.

Yousuf, A., & Najeeb-ud-din, H. J. O. R. (2016). Effect of gain compression above and below threshold on the chirp characteristics of 1.55 µm distributed feedback laser. *23*(6), 897-906.

Yvind, K., Larsson, D., Christiansen, L. J., Angelo, C., Oxenlwe, L., Mrk, J., Birkedal, D., Hvam, J. M., & Hanberg, J. J. I. P. T. L. (2004). Low-jitter and high-power 40-GHz all-active mode-locked lasers. *16*(4), 975-977.