CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Semiconductor injection lasers have become very versatile and important sources of coherent radiation for a variety of applications. Particularly, they are of great interest as transmitters for high bit-rate fiber optics communication systems [1,3]. They have also found applications in optically controlled microwave circuits such as switches [4], injection-locked oscillators [5] and optical fiber delay-line filter networks [6]. The first laser diodes were made of GaAs/AlGaAs and operated in 0.8 μm wavelength region. Later InP/InGaAsP laser diodes were developed and are now dominant since they operate in the 1.3 - 1.5 μm wavelength window. The latter devices are preferred for advance telecommunication applications because of the lower loss in single mode fibers at longer wavelengths. In order to realize long distance, it is necessary both to launch enough optical power into the core of the optical fiber and to reduce the loss due to the optical fiber. As far as these criteria are concerned, the laser diode has an advantage of more than two orders of magnitude over the light emitting diode (LED). The superior spatial coherency of laser diodes permits the launching efficiency into the core of the single mode fiber with a diameter of less than 10 μm to more than 50%. At the same time, the threshold of the laser diode has also been drastically reduced as shown in Fig. 1.1 [7]. First of all, CW (continuous wave) operation is made possible by using GaAs/AlGaAs double-heterostructure (DH) laser diodes. The Quantum well (QW) laser diode, further more, allows low current density operation to several hundreds of A/cm². More recently, the strain layer quantum well (SL-QW) laser diode, which includes Indium in its composition,
Fig. 1.1 Decrease in threshold current densities for various laser diode structures with year.
reduced the current density even further. Further improvement in semiconductor laser performance is expected with the introduction of quantum confinement in more than one dimension [8], resulting in quantum wire (QWR) and quantum dot (QD) laser structures. In particular, QWR and QD lasers were predicted to exhibit extremely low threshold currents in the μA range [9,10], higher modulation bandwidths, narrower spectral linewidths [11] and reduced temperature sensitivities [8] compared to their QW laser counterparts. These properties will make such low-dimensional diode lasers particularly useful in applications involving integration of a large number of lasers on a single chip and integration of diode lasers with low power electronics, e.g., computer optical interconnects, optoelectronic signal processing and optical computing. Because of the many advantages mentioned above, it becomes essential to carry out an in-depth analysis and to study the various characteristics of the semiconductor laser. The various type of laser models and their methods of construction have been developed in parallel with the progress in laser diodes. The models are broadly classified as static and dynamic models.

Static modeling is potentially a tool of great value as it can be used to illustrate the effects of material and structural parameters on device behaviour under steady state conditions [12]. The validity of these models is strongly dependent on specific laser structures to which they are applied. The model is constructed by considering the semiconductor laser system to be consisting of two parts: i) the optical field that can be represented by the set of photons in individual modes and ii) the electrical section of the device that can be represented by the set of free-charge carriers injection into the active region. The mutual interaction of the two subsystems can be represented mathematically [13]. The coupling mechanism between photons and charge carriers can be visualised by examining the graphical representation shown in Fig.1.2 [14]. Determination of these functions is the basic step of a laser structure analysis. The static model makes possible prediction of major properties of lasers directly from known material parameters. For a given
Fig. 1.2 Graphical representation of the laser model showing properties and coupling taken into account.
current, the current density distribution, the temperature profile, the carrier
density profile, the intensity distribution and mode amplitudes can be
obtained. It is possible to effectively apply the model to more sophisticated
laser structures such as the Distributed Feedback (DFB) laser [15].

The understanding of the dynamic behaviour of semiconductor
lasers is of major importance [16] for their applications in high speed data
transmission systems as well as for picosecond optoelectronic signal
processing. This can be studied by taking into account the time dependence
of the electron and photon rate equations. The solutions of these rate
equations are used to study properties which set the limit on the high speed
modulation capability such as the transient response, maximum switching
speeds and the maximum frequency. These coupled non-linear equations have
been solved numerically and by using some approximations, they have been
reduced to a form that can be solved analytically [16-19]. A good number of
research papers were published in the 80’s on the theory of spectral dynamics
and transient behaviour of semiconductor lasers, taking into account effects
like index and gain non-linearities, multimode spikes and period doubling
[20-26]. The study of the effect of chirp, which is an undesirable wavelength
shift that causes a dispersion penalty in high speed direct detection systems
has also been studied using this approach [27-32]. Dynamic modeling in the
recent past has been extended to more advanced laser structures viz quantum
well lasers [11] and DFB lasers [33]. The theoretical results in most cases
have been validated by experimental observations [34,35]. A number of
analytical and numerical techniques have been used to simulate the dynamic
characteristics of various laser types. For example, the Transmission Line
Laser Model (TLLM) is a dynamic, multimode, highly accurate time-domain
model that has been successfully used [36-38]. However these methods suffer
from the following limitations:

1. Specialised software is needed for the analysis.
2. They are not suitable to the inclusion of substrate and package
   parasitics along with the elements in the drive circuit.
3. Inclusion of device-circuit interactions in the calculations of response characteristics is not possible.

An alternate approach that overcomes these limitations is to transform the rate equations into a circuit model which can then be solved using standard circuit analysis techniques. With this approach the small signal as well as large signal circuit models of the semiconductor laser diode have been successfully constructed [39,40]. The main advantages of using equivalent circuit models are as follows

1. Standard circuit analysis packages [41] such as SPICE can be used to determine the device response.
2. The circuit model gives an intuitive feel of the physics of the device. As each of the elements in the model has a physical interpretation, the dynamic operation of the laser can be easily visualised.
3. The circuit model can be constructed so as to include information about the I-V characteristics of the laser diode and its space-charge capacitance.
4. It can be easily interfaced with the parasitics network enabling terminal impedences and device-circuit interaction to be determined.

1.2 THEORY OF CIRCUIT MODELING

This section is devoted to the study of various circuit models of semiconductor laser diodes designed so far.
1.2.1 Junction capacitance effect on turn-on delay of injection lasers

Initially the equivalent circuit model was used in the study of the effect of junction capacitance on the turn-on delay of injection lasers [42]. For the GaAs-Al$_x$Ga$_{1-x}$As double-heterojunction laser that was used with a large junction over the entire wafer presenting a space-charge capacitance comparable to the diffusion capacitance $C_d$ of the junction, the equivalent circuit is shown in Fig.1.3. Further, Dumant et al [43] included the input drive network to the equivalent circuit to study small signal modulation of double heterostructure laser diodes.

1.2.2 Circuit models for packaged laser devices

Following the realization of practical optical fiber transmission systems, serious attention was paid to the effective packaging of laser diodes in order to make devices easy-to-handle, rugged and reliable [44]. The parasitics associated with the mounting and packaging of the laser diodes limit the modulation capabilities by low-pass filtering the signal. The equivalent circuit representation was hence used as a powerful tool for the optimum design of optical transmitters as well as in the investigation of modulation capabilities. The parasitic element values were determined from the measured impedance of each element and were found to be in good agreement with calculated impedance values, thus indicating the applicability of the circuit modeling technique to the circuit design of practical transmitters.

1.2.3 Circuit representation of spontaneous emission and self pulsations effects

The intrinsic electrical equivalent circuit of a laser diode is derived from the coupled rate equations [45]. By this approach, the laser diode in its
Fig. 1.3 The diode equivalent circuit.
basic form is modeled by a parallel RLC circuit. The element values depend on the device parameters [46]. However, fundamental phenomena such as effect of spontaneous emission into the lasing mode and saturable losses are not accounted for in the model. These effects are taken into account in the modified version of the model presented by Katz et al [47]. The photon rate equation of the semiconductor laser diode is modified by adding the spontaneous emission term $\beta(N/r)$ whereas the electron rate equation remains unchanged.

1.3 MODELS PROPOSED BY TUCKER

1.3.1 Large signal case

The models for the laser diode that were described so far do not include the effects of high level injection, carrier degeneracy and non-radiative recombination. These effects have been taken into account in the equivalent circuit presented by Tucker [48] for a double heterojunction laser operating below threshold. Considering the energy band diagram of N-P heterojunction [Fig.1.4], neglecting continuity and assuming smooth energy transition across the junction [49,50], the voltage applied to the junction $V_j$ is given by

$$qV_j = (F_c - E_c) + (E_v - F_v) + E_g \quad (1.1)$$

$$\frac{F_c - E_c}{KT} = \ln \left( \frac{N}{N_c} \right) + \alpha_1 N \quad (1.2a)$$

$$\frac{E_v - F_v}{KT} = \ln \left( \frac{P}{N_v} \right) + \alpha_2 P \quad (1.2b)$$

$\alpha_1$ and $\alpha_2$ are constants. If the concentration of ionised acceptors is characterised by $N_A^*$, then the requirement of charge neutrality in the active layer is satisfied by the expression

$$P = N + N_A^* \quad (1.3)$$

using

$$\frac{N_A^*}{N_A} = 1 - \frac{\gamma P}{N_v} \quad (1.4)$$
Fig. 1.4 Energy band diagram of N-P heterojunction (not to scale).
and assuming equilibrium condition we get [48]

\[ P_0 \left( 1 + \gamma \frac{N_A}{N_v} \right) = N_0 + N_A \]  

(1.5)

for \( P = P_0 \) and \( N = N_0 \) at equilibrium and the acceptor impurity concentration denoted by \( N_A \). The concentration of donor atoms are neglected under the assumption that the p-type active layer is weakly compensated and the relation between the excess carrier densities \( n \) and \( p \) are worked out as:

\[ p \left( 1 + \gamma \frac{N_A}{N_v} \right) = n \]  

(1.6)

Considering both radiative and non-radiative components as well as the displacement current and by neglecting effects of space charge capacitance, the diode terminal current \( I \) is derived.

\[ \text{Hence } I = I_1 + b I_1^2 + \tau_{ns} \frac{dI_1}{dt} \]  

(1.7)

where \( I_1 = q A d n/\tau_{ns} \), \( b = B_1 \tau_{ns}^2/q A d \) and \( \tau_{ns} = (\tau_s^{-1} + \tau_n^{-1})^{-1} \).

\( \tau_s \) and \( \tau_n \) represent the radiative and non-radiative recombination carrier lifetimes, respectively. \( A \) and \( d \) are the area and thickness of active-layer respectively. The equation reduces to \( I = I_1 + b I_1^2 \) under steady state conditions. Further,

\[ B_1 = B/(1+\gamma N_A/N_v), \text{ (B is a constant)} \]  

(1.8)

The diode junction voltage can be expressed in terms of the electron density in the active layer. Therefore by substituting equations (1.2), (1.5) and (1.6) in (1.1), the voltage across the junction becomes,

\[ V_j = V_1 + V_2 + V_3 \]  

(1.9a)

where

\[ V_1 = V_T \ln \left( 1 + n/N_0 \right) \]  

(1.9b)

\[ V_2 = V_T \ln \{1 + n/(N_A + N_0)\} \]  

(1.9c)

\[ V_3 = V_T (a_1 + a_3)n \]  

(1.9d)

\[ a_3 = \alpha_2 / (1+\gamma N_A/N_v) \]  

(1.9e)

\( V_T = KT/q \) is the thermal voltage.
The junction voltage can therefore be represented by three series-connected circuit elements with voltage drops $V_1$, $V_2$, $V_3$ respectively. The first two of these elements represent classical shockley p-n junction diodes (D1 and D2) in a DH laser structure. The current through the DH structure is given by

\[ I_1 = I_{01} \exp\left(\frac{V_1}{V_T}\right) - 1 \] (1.10a)

or

\[ I_1 = I_{02} \exp\left(\frac{V_2}{V_T}\right) - 1 \] (1.10b)

where $I_{01} = qA_d N_o/r_{ns}$ and $I_{02} = qA_d (N_A + N_o)/r_{ns}$. The third series connected element $R_e$ in the circuit is got from equations of $I_1$ and $V_3$.

Hence

\[ I_1 = \frac{V_0}{R_e} \] (1.11a)

where

\[ R_e = (\alpha_1 + \alpha_2) N_o V_T / I_{01} \] (1.11b)

Fig.1.5 shows the large -signal circuit model of the junction. The model has been obtained from equations (1.7) and (1.9-1.11). The resistance $R_e$ in series with the two shockley diodes models the carrier degeneracy and resistance $R_g$ models the diode ohmic regions. A current generator in the circuit that is proportional to $dI_j/dt$ represents the charge storage effects.

1.3.2 Small-signal analysis

Linearisation of the equations described in the above section, in turn, yield the small-signal model of the heterojunction laser illustrated in Fig.1.6 the element values of which are calculated to be:

\[ R_d = R_e + R_{01} + R_{02} \] (1.12)

\[ R_1 = R_d / 2bI_1 \] (1.13)

\[ C_d = \frac{r_{ns}}{R_d} + C_s \] (1.14)
Fig. 1.5  Large-signal circuit model of the DH laser diode.
Fig. 1.6 Small-signal circuit model of the DH laser diode.
Capacitance $C_d$ can be neglected at low frequencies. The input resistance can be given by

$$R_{in} = R_s + R_T, \quad \text{(1.17)}$$

where

$$R_T = R_d/(2bI_1+1) \quad \text{(1.18)}$$

The resistance $R_s$ models the ohmic regions which includes contributions from lead resistance, bulk resistance in the high-band gap materials, and the effective resistance of the near-ohmic $p^P$ isotype heterojunction.

To demonstrate the applications of the equivalent circuit models, the large-signal and small-signal models were used to compute typical transient and small signal electrical characteristics for laser diodes operating below threshold. The calculated characteristics agreed well with previous experimental and theoretical data.

1.3.3 Model for laser operating below and above threshold

The circuit model designed by Tucker was extended to the large signal case for the injection laser operating below and above threshold by the same author [51]. Although researchers had previously studied the effect of driving parasitics, the approach was to analyze the drive circuit and the rate equations separately and then the results of the two analyses were combined [52]. However, the model proposed by Tucker analyzes the rate equations as well as the driving circuit together in a way that the electrical and the optical
characteristics of the device can be determined in a unified manner. By using the general purpose circuit simulator SPICE2 for the first time [51], the model was simulated and a number of laser response characteristics were illustrated. Effects of turn-on-delay, damped relaxation oscillations and spontaneous emission co-efficient $\beta$ were studied. Hence the application of the model in the computer aided design of complex laser switching and modulation circuits became evident.

1.4 MODELING OF THE INTRINSIC INTENSITY NOISE OF LASER DIODE

Intrinsic intensity fluctuations in semiconductor lasers are caused by quantum-statistical photon generation and electron-hole recombination within the lasing mode. Also termed as quantum noise, these intensity fluctuations in specific applications may significantly degrade system performance. Therefore, modeling of the noise source becomes essential for the accurate representation of the laser diode. The approach is to extend the small-signal electrical circuit of the laser diode [47] to include intrinsic noise sources by adding the noise source terms $f_N(t)$ and $f_S(t)$ for the electrons and photons respectively in the rate equations [53]. Assuming $f_N$ and $f_S$ to have shot-noise character, the spectral and cross-spectral densities of the noise terms are calculated. In terms of the spectral densities the intrinsic shot noise is modeled by the voltage and current noise sources $i_n$ and $v_n$ as seen in the circuit model of Fig.1.7. The current noise source $i_n$ represents the shot noise due to carrier recombination and the voltage noise source $v_n$ models the random process of stimulated emission. The usefulness of this model has been demonstrated by a full-fledged study of the modulation and noise characteristics of the semiconductor laser [53].
Small-signal model of a semiconductor laser diode.
The input signal is the modulation current $i_{j}$ or modulation voltage $V_{j}$. The optical output signal is directly proportional to $i_{L}$. The intrinsic shot noise is modeled by the voltage and current noise sources.
1.5 INCLUSION OF THE LATERAL DIFFUSION EFFECT IN THE CIRCUIT MODEL

Effects of lateral carrier diffusion were neglected in the models described so far. However, as lateral diffusion due to a nonuniform distribution of electron density in the active layer causes significant damping of the relaxation oscillations which further results in a reduced magnitude of the resonance peak in the small-signal frequency response, there arises a need to provide a straightforward explanation of the relative significance of diffusion damping. A detailed small-signal analysis was therefore carried out in reference 54 that reduced the rate equations to a form that includes the \((1-c_P)\) scaling factor in the gain term when compared to the conventional single-mode rate equations for a laser with no lateral diffusion and with constant electron density \(N\) across the active layer.

1.6 COMPARISON OF LASER DEVICE STRUCTURES

Circuit models of semiconductor laser diodes are strongly dependent on device structures. For example, in some buried heterostructure devices, effects of parasitic resistance and capacitance in the device chip are more pronounced where as it is observed that the parasitics are small in ridge waveguide lasers. Hence an indepth study of the differences between the various structures is essential. The circuit modeling approach has been used to establish the precise origin of these elements which significantly influence the small-signal frequency response and large-signal time domain step response [55]. Tucker and Kaminow analyzed and compared the effect of these elements on the high frequency modulation characteristics of InGaAsP ridge waveguide and of edge mesa buried heterostructure (EMBH) lasers. The results showed that the turn-off transient is strongly affected by the parasitics and hence is a major limitation speed of the EMBH laser in PCM applications.
1.7 RECENT DEVELOPMENTS

Although technological progress has been accompanied by a considerable number of publications on the circuit theory of semiconductor lasers, explanation of more exotic effects calls for rather detailed circuit models. Recently, a circuit model for laser frequency modulation due to changes in carrier density and temperature effects was derived [56]. A circuit theory of laser modulation and noise for the single-element as well as the more realistic multielement laser diode has been established by Arnaud [57,58]. Another approach has been the design of models based on the approximation of the Fermi integral [59]. The circuit modeling approach has also shown potential applications in the computer aided analysis of coupled semiconductor lasers [60] and laser diode arrays [61]. A totally new technique very recently evolved has been the combination of the transmission line model with that of the circuit model [62].

The rapid advances and many applications of the circuit modeling technique applicable to semiconductor lasers that have been described in this chapter give a clear indication that even though wave guiding effects may not be easily incorporated in the models, compared to the many advantages this is of minor importance in the analysis of index-guided lasers. In order to maintain pace with the rapid developments in this field, analysis of more advanced laser structures using this simple technique will pose challenges in the future.

1.8 SCOPE OF THE PRESENT WORK

In the present study the circuit modeling approach has been used to obtain models for various laser structures, namely, the double heterostructure laser and quantum well lasers. It is envisaged to report the present work in the following chapters:
In Chapter 2, the circuit model of a single mode double heterostructure laser has been derived from the rate equations. The model is simulated using PSPICE circuit simulator for steady state and transient conditions. The effects of spontaneous coupling co-efficient $\beta$, package parasitics and modified gain compression parameter on the response of semiconductor laser (SL) are studied. In addition, a model for the laser diode based on multimode rate equations has been developed. The model has been used along with the delay line model for the optical fiber and an optimised diode detector model for the receiver to simulate a digital optical data link. As an example of the application of the model, eye diagrams were generated to study the effect of fiber dispersion. Further, the effect of wavelength shift or "Chirp" has been investigated by using the circuit equivalent model of the chirp rate equations.

Chapter 3 deals with the modeling of the QW laser. A two port circuit model for the QW laser has been developed from the rate equations with emphasis on the physical principles. The phenomena of the recombination process of electron-hole pairs and the light wave resonance in the active region have been incorporated into the model. The model is simulated and validated by comparing dc and transient analysis with theoretical results and published data. This model in conjunction with the optical fiber and photo detector model constituting an optical link has also been simulated. The effect of RC time constant on photodetector response is studied. In addition, the system performance has been investigated for input pulse formats corresponding to 3 level and 2 level alternate mark inversion (AMI) pulses. Eye diagrams are generated for a non return to zero (NRZ) pulse sequence for a bit rate of 1Gb/s. Further more, a small signal model of the QW laser diode is simulated and the frequency response is obtained. It provides a modulation bandwidth of about 0.1 GHz.

Pico-second pulse generation in QW semiconductor lasers using the gain switching (GS) technique is gaining popularity since the enhanced
differential gain in these lasers is responsible for obtaining ultrashort pulses. So far, the GS characteristics of QW lasers have been investigated either experimentally or theoretically by the numerical solution of the rate equations. In Chapter 4, circuit models corresponding to the multiple quantized state transitions (QST) for the generation of picosecond pulses from QW lasers, have been developed by considering both linear and non-linear gain co-efficients and picosecond pulses of 7 and 2 psec FWHM (Full Width at Half Maximum) corresponding to the second and third quantised state transitions respectively were observed by simulating the models. A remarkable reduction in the output pulse width that is observed for the third quantised level transitions demonstrates the significance of higher subband transitions for the generation of ultra short pulses. Effects of cavity length and number of wells on the output pulse shape were also analyzed. Further more, a model to represent Well- Barrier (W-B) hole burning which is responsible for additional damping in the QW laser has been developed. The model is simulated for various values of $\eta$ (ratio of carrier density in the barrier to the carrier density in the well). The threshold current was observed to have been increased from about 1.5 to 3.0 percent for $\eta=1$ and $\eta=2$ respectively, compared to the QW laser model without any hole burning effect.

Lastly, the various circuit models developed during the course of the work and the results obtained have been summarized in Chapter 5.